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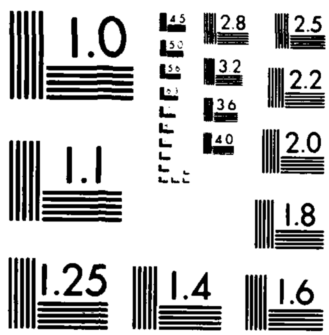

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An Information Processing Approach to the Study of Data Entry Skills: The Effects of Representation Rules and Coordination Requirements

Technical Report

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and Emanuel Donchin

Prepared for:

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Current models of complex psychomotor skills conceptualize the generation of skilled movements as being governed by high level motor programs or schemas in long term memory that are developed with practice. In the present study we examined the nature and role of such high level representations in the context of the acquisition and operation of a complex transcription skill. More specifically, we investigated the importance of the rule employed to associate letters with their motor productions in a typing skill based upon a newly designed two hand chord keyboard. This keyboard comprises(continued on reverse)

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two, separate, 5-key panels (one for each hand). A letter on each panel is entered by typing a motor chord composed of one to five fingers pressed together. Each panel is capable of producing the full set of the alphabet, and hence in principle constitutes an independent typewriter. If skilled transcription can be performed in parallel, operators can type two independent texts simultaneously on this system.

The present experiment compared performance and learning using three coding principles to map letters to fingers on the two panels: a) Spatial-key arrangement, b) Hand symmetry, and c) Combination of the two (correspondence in terms of both principles is preserved if the panels are tilted upright to a vertical position). The results showed a pronounced influence of representation mode on the coordination of hands, with a clear superiority to coding by spatial arrangement over hand symmetry. A further benefit was obtained with the combined vertical posture. The effects of representation mode increased with practice nd were largest on the last session of training. Hence, improvement of performance with the advance of skill does not imply a reduction in the role of high level representation. Converging evidence from electrophysiological records of brain event related activity showed that in the task of transcription, bottlenecks leading to differences in the efficiency of skilled performance arose as much from the contribution of encoding and retrieval processes as from motor and response coordination factors. These results are discussed in light of current issues in the study of complex skills, and the theory of processing efforts.

AN INFORMATION PROCESSING APPROACH TO THE STUDY OF DATA ENTRY SKILLS:

THE EFFECTS OF REPRESENTATION RULES AND COORDINATION REQUIREMENTS

Final Technical Report FY-83

Daniel Gopher, Walter Koenig, Demetrios Karis, and Emanuel Donchin

Cognitive Psychophysiology Laboratory

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FORWARD

The present report summarizes experimental work that was conducted at the University of Illinois during the first of a three year research program. The work was conducted while Daniel Gopher was on sabbatical at the Cognitive Psychophysiology Laboratory. At the present the project continues both at Illinois and at the Technion-Israel Institute of Technology. A partial report on this work was contained in an earlier technical report entitled, "Hands Coordination in Data Entry with a Two-Hand Chord Typewriter" (CPL 83-3, June 1983). The present report is more complete and comprehensive. It is based on a larger sample, additional measures, and a more detailed analysis of the initial measures. For the clarity of description, some of the figures already presented in the earlier report are repeated.

INTRODUCTION

Current models of complex psychomotor skills conceptualize the generation of skilled movements as being governed by high level motor programs or schemas (e.g., Schmidt, 1975; Kelso, 1982; Klapp & Greir, 1978). These programs are developed with practice and maintained in long-term memory. The nature of these representations, their main faculties and role in the elicitation and conduct of movement, as well as the process of their emergence in the course of training, are focal issues of research and scientific contemplation. Examples of more specific questions in this problem area are: the characteristics of action plans, generalization of plans across performing organs, the role of spatial and proprioceptive elements in their formation, and the impact of plans on the guidance of behavior early and late in training.

In the present paper we examine the nature and role of representations in the context of the acquisition and operation of a complex transcription skill. We investigate the importance of the rule employed to associate letters with motor productions in a typing skill based upon a newly designed two-hand chord keyboard (see Figure 1). This keyboard comprises two separate 5-key panels (one for each hand). A letter is entered on each panel by typing a motor chord composed of one to five fingers pressed together. Each panel is capable of producing the full set of the alphabet, and hence, in principle, constitutes an independent typewriter. If skilled transcription can be performed in parallel, operators can type on this system two independent texts simultaneously.

Insert Figure 1 About Here

Because letters on the two panels are represented by their respective motor chords (finger combinations), one immediate question is, what is the best principle to represent the same letter on the left and right hand panels to maintain consistency and compatibility across hands? A study of this issue is exploring, in essence, the way in which motor chords (letter codes) are represented and organized in long-term memory, and the effects of the properties of representations on the coordination of hands in simultaneous typing. There is little direct information in the present literature to answer these questions. One group of researchers has placed a major emphasis on the end location of the movement, and, therefore, has given a dominant role to spatial characteristics at the upper level of the action plan hierarchy (Kelso, 1982; Turvey, 1977; Gopher, 1984). These authors go so far as to promote a vision based theory of action (vision is, of course, responsive to the external spatial properties of the movement). Another group attributes the prime importance to internal characteristics of movement. They center their modeling efforts on forces and tensions operating at the muscle and joint levels of the performing organ, leading in turn to an emphasis on proprioception and muscle information as the basis of motor plans (e.g., Bizzi, Polit, & Morasso, 1976; Cooke, 1979; Hallet, Shahani, & Young, 1975). In the works of both groups, single rather than coordinated movements of the two hands have been the main concern, and the relationship to the properties of an underlying semantic structure that is

central in transcription skills is naturally absent.

Given that the two panels of keys of the two-hand keyboard are positioned horizontally side by side (see Figure 1), there are two mapping rules that suggest themselves. They also appear to be linked with the two loci of emphasis mentioned above. One rule is Hand Symmetry (HS); the same fingers of the two hands represent the same letter (e.g., if a chord composed of the thumb and index fingers represents the letter "A" on the right hand panel, the same fingers are used to enter "A" on the left panel). An alternative rule is SPatial Arrangement (SPA); the same keys on each panel represent the same letter (e.g., if the keys on each panel are numbered sequentially from left to right, then, for example, keys 1 and 2 on both panels are used to enter the letter "A"). Coding by hand symmetry is based upon a body reference point. It maps letters to both hands in accordance with the anatomical structure of the performing organs. It is more closely linked with an emphasis on proprioception and muscle information. In contrast, spatial arrangement relies on an external, objective, reference point, and letters are specified by the pattern of pressed and unpressed keys. Application of each of these coding principles introduces incompatibility in terms of the rule that has not been employed. Under HS, the patterns created by the same letters are mirror images of each other. When SPA is applied, different fingers are used to enter the same letters on the two panels (see Figure 2). Are both representation rules feasible? Can subjects be instructed as easily to adopt one or the other? Which rule will lead to better performance? Is one type of conflict more interfering to performance than the other? These are the main questions that were addressed in the present experiment, which contrasted the

performance of two groups of subjects, each trained under one of the rules.

Insert Figure 2 About Here

While application of HS and SPA create representation conflict when the keyboards are placed side by side, these conflicts are resolved if the panels are tilted upright to a vertical posture (see Figure 2). In this posture the principles unite and correspondence according to both of them is preserved. Would such unification have any advantage over the better of the two basic rules? A third group of subjects was trained in this COmbined Vertical condition (COV) to investigate this question.

Although the main emphasis in the present study is on the influence of representation modes, the more general elements involved in the acquisition and operation of data entry skills under this paradigm should not be ignored. Acquisition and operation of typing skills are a topic of several recent basic research and application efforts (e.g., Cooper, 1983; Gopher, 1984; Gentner, 1983). The new data entry system diverges from the traditional one in many of its basic dimensions, and as such enables several interesting comparisons. In a rough analysis, one clear requirement of the new system is the feasibility of committing to memory the 26 (or possibly 52) codes of letters. Another component is the production by each hand of chord combinations that vary in complexity and difficulty. Finally, there is the requirement to coordinate the two hands in simultaneous data entry. Thus, there clearly exists heavy memory and retrieval requirements, motor and biomechanical constraints, as well as hand coordination problems on the retrieval, execution and timing levels. All of these factors may influence

learning rates, response times, and the number and type of errors. It is important to attempt to specify the differential influence of each of these elements and its relative share in problems of performance at different stages of training. This is the second focus of interest in our study. To examine these questions convergent data from performance measures have been collected together with cognitive psychophysiological measures of Event-Related Brain Potentials (ERPs).

METHOD

Subjects

Eighteen right-handed male college students who spoke English as their native language served as subjects. Event-related brain potential data were recorded from 15 subjects. Subjects were paid for their participation at a rate of $3.50 per hour, and also received additional bonuses (described below) based on their performance. Subjects were randomly assigned to the three experimental groups.

Apparatus

The experiment was governed by a PDP 11/40 computer system. The letter stimuli were presented on a plasma panel display and responses were entered through the two-hand chord keyboard and recorded directly onto magnetic tape. The keyboards were positioned horizontally for the hand symmetry and spatial conditions, and vertically for the combined condition. Hand rests were added for the vertical position. The keyboards were situated between the subject and the display.

Letters were 1/2 cm tall and 1/4 cm wide. In dual presentations the letters were 4.2 cm apart. The line of sight distance was approximately 60 cm (thus, the angle for a single letter was approximately half a degree, and the visual angle between the stimuli in the dual presentations was approximately 3.75 degrees). In addition to the behavioral measures, electrophysiological measures were taken during meetings three through seven. These will be described in detail below.

Procedure

Subjects took part in a total of seven ninety minute experimental sessions. The first session was devoted to code acquisition and initial familiarization. Subjects were introduced to the data entry keyboard and presented with charts describing the letter codes relevant to their respective conditions. They were instructed to memorize the 26 letter codes for the right and the left hands. Subjects were not given any specific method of memorization, and could explore the codes by pressing chord combinations on the keyboard. As they pressed the various chords the respective letters would appear on the left or right side of the display, depending on which keyboard was used. Subjects were required to be able to produce any letter code without the aid of the charts before they were allowed to begin the formal experimental phase.

Following the first meeting, and throughout the six remaining sessions, the subjects were required to respond as quickly as possible to letters presented on the display by entering the appropriate codes. Letters were presented on the left or right sides of a fixation point, or dually. Subjects were required to respond to letters presented on the left with the

left hand, to letters on the right with the right hand, and to dually presented letters with both hands.

Trials were organized into mixed or dual blocks. In the mixed blocks the subjects were presented with equal numbers of single left, single right and dual letter presentations. In these blocks the full 26 letter alphabet was used. Trial types and letters were generated randomly from trial to trial. In the dual blocks only dual letter trials were presented. In these blocks a limited set of only eight letters was used. The trial format was the same for both the mixed and the dual letter blocks (see Figure 9). The trial began with a warning dot which appeared 800 msec prior to the appearance of the letter. The dot appeared in the location of the expected letter. Two dots appeared in the case of dual presentation. Thus the subject was primed on the type of trial, the location of presentation, and performing hands. Following the 800 msec warning interval, a letter or pair of letters was presented for 300 msec, followed by a 1700 msec response interval. Feedback was then presented. This feedback occurred at the end of the response interval and was in the form of a plus for a correct response and a minus for an incorrect response. The feedback, like the warning dot, appeared at the location of the respective letter.

In each of the six experimental sessions there were eight mixed blocks consisting of 52 trials per block followed by two dual (limited set) blocks of 64 trials each. In a given meeting there was, therefore, a total of 416 mixed trials and 128 dual trials resulting in a total of 544 trials per meeting. Subject performance was motivated by a bonus system in which both speed and accuracy were emphasized. Subjects received a bonus of $1.50 for every improvement of 10% in their response time, provided the percentage of

errors did not exceed 5%.

A control task was also included in meetings two, four, and seven. This task tested simple response time on the keyboard. A trial in the control task involved the presentation of the single letter "H" which had the same code across all conditions (index and ring fingers). Two blocks of 32 trials each were presented, one for the right hand and one for the left hand response.

RESULTS

The description of results is divided into three main sections. We begin by presenting *learning curves* and performance levels of the three groups based upon response time measures. The second section presents a summary and analysis of errors in data entry. In the third section we describe the main findings of the electrophysiological recording.

Initial Acquisition

In the first meeting subjects were introduced to the system and were given the chart of two hand letter chords for their respective group to memorize (Figure 2). In this phase they could produce single letters or pairs of letters on the screen by pressing the correct codes. No specific learning or memorization method was suggested by the experimenter. Subjects' progress was tested every 20 minutes by asking them to produce left or right hand letters upon request. The general finding was that subjects in all groups were able to commit all codes to memory within 30-45 minutes. In a following debriefing they reported a wide range of spontaneously developed rules and subjective mnemonics that were called upon

to help memory.

Response Times to Different Letters

Chord combinations for the 26 letters differed from each other in the identity and number of fingers, and the combination of pressed and unpressed keys. As a result they created a gradient of difficulty. Following earlier studies by Seibel and Dvorak (Seibel, 1972), the easier chords were assigned to more frequent letters in English (Pratt, 1939). Appendix B presents figures with the full dictionary of codes, and the average response times for letters in the three experimental groups at the last training session. Separate averages are given for the left and right hands in single and dual letter trials. A wide range of differences among response times of easy and difficult letters can be observed on all 4 averages. The ranges between letters over all experimental groups were 333.0, 395.0, 291.7, and 396.4 msec for single right, single left, dual right, and dual left hand responses respectively. In all cases they were highly significant ($p < .001$). Note that the range was larger on the left hand both in single and in dual task conditions, and smaller on dual right than on single right responses.

Learning Rates and Performance Levels

Six main measures of response time were computed for the performance of each subject in a training session. In mixed blocks, separate averages across the 26 letters and all blocks of the same session were computed for the right and left hands, in single and in dual letter trials, leading to a total of 4 averages per session: Single Left (SL), Single Right (SR), Dual Left (DL), and Dual Right (DR). Two additional averages were computed for left and right hand responses in dual blocks with a limited set of letters

(DLL and DLR). Figures 3 and 4 depict the learning curves of the HS, SPA, and COV experimental groups in single, and in dual letter trials.

Insert Figure 3 & 4 About Here

Several outcomes are worth noting in these figures. Performance of all groups on all measures demonstrates a steep improvement with training (note that averages for only 6 meetings are presented, because formal data were not collected in the first meeting). Clear differences can also be observed between single and dual letter presentations, performing hands, letter set size, and the coding principles that signify experimental groups. The statistical significance of these differences was tested by several analyses of variance. An overall 5 factors analysis was conducted on: Groups (3) x Sessions (6) x Hand (2) x Condition (single, dual) x Set size (full, limited). It was followed by separate analyses for single letter trials, dual letter trials, single letter performance together with the first of the two responses in dual letter trials, and a separate analysis for the second of the two responses in dual letter trials (the time to complete a pair). In each analysis all other factors maintained their factorial structure. The following is a review of the main findings of these analyses.

Sessions: A main effect of reduction in response times with the progress of training was strong and highly significant in all analyses. In single letter trials the average decrease in response times during the 6 sessions was 390 msec ($F(5/75) = 152.8$, $p < .001$). In dual letter trials overall improvement was of the same magnitude ($F(5/75) = 104.1$, $p < .001$).

There was no interaction between sessions and the operating hand or the coding principle group in single letter trials. In dual letter entries, the session variable had significant interactions with all other variables, namely, groups, hands, and set size. We describe these interactions below in the discussion of these variables.

Hands: As can be observed in Figures 3 and 4, left hand responses were faster than those of the right hand both in single and in dual letter trials. The overall left hand average in single letter trials was 755.2 msec. The average for the right hand was 812.9 msec ($F(1/15) = 176$, $p < .001$). In dual letter presentations the averages for the two hands were 905.7 and 1113.3 msec, for the left and right hands respectively ($F(1/15) = 39.8$, $p < .001$). In addition, significant interactions were obtained in dual letter trials between hands and session ($F(5/75) = 11.8$, $p < .001$), and between hands and letter set size ($F(1/15) = 65.5$, $p < .001$). The interaction with sessions resulted from the fact that improvement on the right hand during the 6 training sessions was larger than on the left hand, 436 versus 328 msec. The obtained interaction with the letter set size variable was due to the larger difference between hands in mixed blocks, which included the full set of letters. The right hand was slower than the left by 274 and 140 msec in blocks with full and limited set size, respectively.

The cause of the difference between hands in dual letter entries is quite obvious. Subjects were unable to enter letters simultaneously, and following the scanning direction of the English language the left hand leads while the right hand completes the pair (in Hebrew this pattern is

reversed). A closer examination showed that in 98% of the trials the left hand moved first in a dual entry. More puzzling is the finding of an advantage of the left hand in single letter trials, which was present in all three experimental groups. Recall that all subjects in this experiment were right handed. Moreover, in single letter trials a warning was given 800 msec in advance of letter presentation. This warning informed the subject both on the operating hand and on the location of the letter, hence giving him ample time to prepare his responses.

To rule out a simple motor factor or an artifact as the basis of these differences we ran a control condition. Subjects were given two additional single letter blocks in sessions 3, 5, and 7. In these blocks, one for each hand, the letter "H" was presented on all trials, thus testing simple response times with no additional processing requirements. The results were again clear and opposite to the above finding. Now it was the right hand that had a small but significant advantage over the left hand (RT for the right hand was 191.2 msec, while for the left is was 202.6 msec, $t(14) = 2.16$, $p < .05$). Fifteen of the 18 subjects in the experiment were run in this condition, and 11 were faster in their right hand responses. In the other four subjects response speeds in both hands were about equal.

Conditions: The time to begin the entry of the first letter in dual letter trials was significantly slower than single letter responses. (The average for singles was 784.5 msec, for first dual, 901.8 msec, $F(3/45) = 17.19$, $p < .001$). A trend for an interaction between session and the condition variable was also revealed as a result of a larger improvement in single letter response times than on the first of the dual letter responses

($F(15/225) = 1.54$, $p = .094$).

Set size: Limiting the number of letters to 8, and blocking them in separate blocks composed only of dual letter trials, had the expected effect on response latency. Entry times for both the first and the second letter in a pair were shorter than in a mixed blocks containing all 26 letters ($F(1/15) = 39.8$, $p < .001$). The interaction between set size and hands was also significant ($F(1/15) = 65.5$, $p < .001$). Table 1 presents the average response times for the dimensions of this interaction.

Table 1 - Average response times (msec) for dual letter entries in dual mixed and dual limited blocks (across groups and sessions)

	Type of Blocks		
Hand	Mixed	Dual Limited	Mean
Left Hand (first)	952.0	859.3	905.7
Right Hand (second)	1226.9	999.6	1113.3
Mean	1089.5	929.5	

We can see that the difference between the two hands is much larger in mixed than in limited set blocks.

Groups: The presentation of results thus far has concentrated on general effects that signify the performance of subjects, with a disregard

to the coding rule to which they were assigned. We turn now to review the specific effects of the representation principle on response times. The majority of these effects can be observed in Figures 3 and 4, and the reader may want to refer back to them as the results of the statistical analyses are described. In single letter trials, if the results of all letters are pooled together, coding principles do not have a significant main or interactive effect on response times. Although the three groups exhibited differences in the same general direction that were observed in dual letter trials, these differences were not statistically significant. RT averages (msec) were: HS, 820.5; SPA, 793.2; and COV, 738.4 ($F(2/15) = 1.35$, $p = .29$). However, if we enter the letter code variable into the analysis, and compare the groups in their performance during the last session (see Appendix B and Figure 5), the differences are highly significant for both hands ($F(2/50) = 4.44$ and 6.47, $p < .01$, for the right and left hand respectively). Duncan post analysis ranking showed for both hands that it was the COV group that differed from the other two.

Differences between groups were most pronounced and statistically significant when the two hands had to be coordinated in dual letter entries. However, they revealed themselves in interactions rather than in a main effect. The most important of the interacting variables was sessions, but its effect was mediated by operating hands and letter set size. As depicted in Figure 4, the three groups started from about similar levels of response times at the second session, but the SPA and COV groups gained an increased advantage over the HS group with the progress of training. At the end of the 7th session the COV group is established as fastest, SPA is second, and HS is slowest. (For the two hands together, $F(10/75)$, [Group x Sessions x

Hands] = 2.1, $p = .037$. For the <u>right hand only</u> (the time to complete dual entry), $F(10/75)$, [Group x Sessions x Set size] = 2.47, $p = .013$; <u>left hand only</u>, $F(30/225) = 1.54$, $p = .042$).

The meaning of these three triple interactions can be clearly observed in Figure 4. The differences between groups are largest on the right hand, in mixed blocks, at the end of training (upper right, Figure 4). They are smaller at the beginning of training, tempered by reduced set size, and less pronounced between the SPA and COV conditions on the left hand (the beginning of a dual hand chord; lower left, Figure 4). To further illustrate the standing of the three groups on the main RT measures at the end of training, we plotted in Figure 5 the results on the 7th session only. The first point in this figure shows the lack of difference between groups

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Insert Figure 5 About Here

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in simple RT (tapping H). There is a step increment in response time with small differences between groups in single letter conditions. Another increment in the latency to begin a dual entry, with now a clear differentiation between groups. Finally, the clearest differences and the slowest average response times are those required to complete a dual chord by the right hand. A separate analysis of the 7th session dual trial data, entering the letter code variable, again yielded highly significant main effects of groups ($F(2/50) = 21.97$ and 44.65, $p < .001$ for the left and right hands, respectively). Duncan post analysis ranking showed that the three groups are significantly separate in the time to complete a dual entry chord.

Dual entry of the same letters

What happens if the same letter has to be entered simultaneously by both hands? The dual limited set blocks were especially constructed to test this question. Pair combinations of only 8 letters were presented in these blocks. Four of the 8 do not create a representation conflict under any of the experimental conditions, and 4 do create either spatial or hand symmetry conflict depending upon the experimental group. The nonconflicting letters were E, N, H, and S. The codes of these letters are composed of chord combinations that are symmetrical around the center (e.g., E is the middle finger, S is entered by the thumb and little fingers; see Appendix B, or Figure 13). Symmetrical codes retain their finger and pattern identity under both spatial and hand symmetry rules. The conflicting letters that were selected, I, A, T, and U, created a conflict under each coding principle in terms of the other rule that had to be ignored (Appendix B; see also Figure 13). All eight letters are among the easier to remember and execute. They were chosen with the intention to minimize interactive influences of perceptual or motor difficulty on the comparison of interest.

The outcomes of the comparison are summarized in Figure 6. Separate bargraphs for each experimental group depict the difference in response times (msec) between conflicting and nonconflicting letters, on the left and right hands.

Insert Figure 6 About Here

Each bargraph represents an average for the respective 4 letters over the last three training sessions.

Although the results for all three groups are presented in Figure 6, the interesting comparison is, of course, between the HS and SPA groups. For COV subjects both types of letters had the same level of compatibility, because for this group consistency in terms of the two principles is always maintained. Their results may serve to calibrate the effects observed for the other two groups. Examination of the combined group results showed about 30 msec advantage in response times on both hands for the group of 4 conflicting letters. It appears that the chord combinations for letters in this group were somewhat easier to perform. The data of the hand symmetry group showed the same direction and magnitude of difference, although it failed to reach statistical significance. Thus, the fact that the same letters created mirror images of each other in terms of their panel arrangement, had little influence on the efficiency of their joint entry. In contrast, the differences between the two types of letters are most dramatically reversed for subjects in the SPA group. Here there is a 75 msec increment in average response times, on both hands, for letters that belong to the conflicting group. When spatial arrangement is employed as a coding principle, dual entry of the same letters do suffer from the requirement to use different fingers. This outcome stands in clear contrast to the general superiority of the spatial over hand symmetry principle in

dual entries that was revealed in our earlier analyses.

Savings in simultaneous entries

One interesting aspect of data entry on the two hand keyboard is the ability of its users to take advantage of its parallel entry capability. To state this differently, is there any saving in simultaneous over single hand entries? Also, is there a difference between the three groups in the ability to interweave responses? To test this question we constructed, for the data of mixed blocks in the last session, measures of relative and absolute savings. Absolute saving was computed for each subject by adding his single letter trials averages for the two hands and subtracting from this sum the average time to complete a dual letter entry. The logic being that the sum of singles is an estimate of the time to enter a pair of left-right letters successively. To compute relative saving, the above absolute difference score was divided by the sum of singles and multiplied by 100, to express it in units of percent savings. The rationale underlying this second measure is that the amount of interweaving should be calibrated relative to the absolute size of the response. Slower RTs are less amenable to a floor effect, hence larger savings in overlap may be, theoretically, easier to obtain. Figure 7 presents the comparison between groups on these two measures.

Insert Figure 7 About Here

All groups show some degree of saving in dual as compared with single successive entries. However, on both measures the HS group was considerably

lower than the other two groups, which were about equal. The statistical analysis of these differences failed to reach the conventional level of significance, possibly due to the small number of subjects. (For relative saving $F(2/15) = 2.86$, $p = .089$; for absolute saving $F(2/15) = 2.11$, $p = 0.15$.)

<u>Analysis of Errors</u>

The overall number of errors in this study was small. Experimental instructions were designed to emphasize accuracy as much as speed. Subjects earned bonuses for increased speed only if they kept their error rates at or below 5%. Computation of errors included both entry errors and missed trials. Recall that subjects were given a total duration of 2 seconds to respond to the currently presented letter(s). If no response was made within this interval a new letter was generated and the trial was counted as a miss. Missed and erroneous trials were discounted from the computation of RT averages.

Table 2 summarizes the distribution of the total number of errors in the three experimental groups. Errors were collapsed over all sessions and all subjects within each experimental group.

Table 2 - Number of errors and missed responses in the three experimental groups

Group	Errors	Miss	Total	Mean	S.D.
HS	887	2297	3184	530.7	183.4
SPA	1549	1183	2732	455.3	130.1
COV	1265	921	2186	364.0	88.[illegible]

As can be seen, the distribution of errors reflects the same general order of groups that was revealed in the analysis of response times. Hand symmetry had the largest number of bad trials ("total" in Table 2) and the COV group had the smallest number. Although this trend failed to reach statistical significance ($F(2/15) = 2.9$, $p > .05$), it clearly precludes the possibility that the observed differences between groups in response times were caused by a speed accuracy tradeoff. It is also natural that the HS group, which had the slowest response times, would also have the largest number of missed letters. If we consider the inability to produce the required response within the allotted time as an indication of difficulties, missed data should not be separated from the general account of errors. It is only separate in a technical sense, because of the absence of an actual response that can be further typified and assessed.

We attempted a closer examination of the entry errors by concentrating on errors that appeared at a frequency greater than 1% in the population of errors. This examination revealed that errors can be generally categorized into two main types: Motor errors and Representation errors. Motor errors

are those that result from faulty activation (or lack of activation) of fingers that can be attributed to biomechanical properties and constraints of the hands. For example, if a chord is composed of 4 fingers it is many times more difficult to restrain the fifth finger that should be held back. Or if the middle and little fingers constitute the required chord, the ring finger joins also. In motor errors the actual typed chord and the desired chord usually comprise different numbers of fingers. They are also not symmetrical; that is, if "N" is typed instead of "H", "H" will not be mistakenly typed for "N".

Representation errors are typically those that manifest confusions between the patterns created by the replaced letters. Most common are left or right shifts on the panel, of chords composed of a coherent group of several successive fingers. Another typical mistake is a complete left right reversal (mirror imagery) in the direction of the desired pattern. Unlike motor errors, it is typical for representation errors to have the same number of fingers in the desired and mistaken codes, and to be symmetrical, if "C" is replaced by "D" then "D" will be replaced by "C". In Figure 8 we display 12 examples of the more frequent motor and representation errors. For the sake of simplicity, all examples are drawn from the vantage point of right hand typing. However, the two hands are not distinguishable in the type of errors.

Insert Figure 8 About Here

The majority of classified errors in all experimental groups were of the motor type. Nevertheless, the three groups differed from each other in the relative frequency of representation and motor errors within their error populations. The percentages of representation errors in the total for each group were 29.6, 41.7, and 19.6 for the Hand Symmetry, Spatial Arrangement, and Combined Vertical groups respectively. It seems that subjects trained under the Spatial Arrangement principle were the most susceptible to pattern confusion errors. With this statement we would like to conclude the present analysis of errors. It is quite clear that a detailed analysis of errors may be an important source of information on the processes in question. However, because of the small number of errors, the small size of the sample, and the special procedures employed to reduce errors, it seems unwise, at this point, to continue the analysis. We defer an attempt for a more comprehensive analysis to a later study with a larger and richer body of errors.

ANALYSIS OF EVENT-RELATED BRAIN POTENTIALS

Recording and Data Collection

Three Ag-AgCl Burden or Beckman Biopotential electrodes were affixed with collodion, or with Grass EC-2 electrode cream, at Fz, Cz, and Pz (10/20 system) and to mastoids by stomaseal adhesive collars. Electrodes were also placed 4 cm to the right and left of Cz along the interaural line. The same type of electrodes were also used as ground and electro-oculogram (EOG) electrodes. The subject was grounded on the forehead, sub and supra-orbital electrodes were used to record the EOG, and linked mastoids were used as

references. Electrode impedance did not exceed 10 KOhm. The EEG was amplified with model 7P122 Grass amplifiers (time constant 8 seconds, upper half-amplitude frequency 35 Hz, 3dB/octave roll-off).

The subject was seated in an air conditioned unshielded room, while the recording and control apparatus were located in an adjacent room. All aspects of experimental control and data acquisition were controlled by a DEC PDP 11/40 computer system (Donchin & Heffley, 1975). Average waveforms and single-trial records were monitored on-line. Eye movement artifacts were corrected off-line using a procedure described in Gratton, Coles, and Donchin (1983). The EEG was digitized at the rate of 100 samples/sec for 2.9 seconds, beginning 100 msec prior to the warning stimulus. This epoch thus included an entire trial, including the warning, the stimulus presentation, the response interval, and ending when the feedback stimulus was presented. The time sequence of a trial, as well as the various

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Insert Figure 9 About Here

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conditions, is presented in Figure 9.

Data Analysis

After subtracting the baseline, peaks were identified in seven time windows (from stimulus onset) at the electrode and polarity given in Table 3. Three measures were recorded by a computer program: peak latency, peak amplitude, and peak to peak amplitude (measured from the previous peak). A letter (or two letters) was presented 800 msec after the warning, and the time windows starting at 800 msec in Table 3 are set back to 0, although the

time from the warning stimulus onset is also given in parentheses.

Table 3 - Description of Peaks Chosen for ERP Analysis

Window	Polarity	Electrode	Component
100-300	negative	Fz,Cz	"N100"
300-650	positive	Pz	"P300"
650-800	negative	Cz	"CNV"*
0-350 (800-1150)	negative	Cz	"PINV"**
350-900 (1150-1700)	positive	Pz	"P300"
900-1300 (1700-2100)	negative	Cz	a late negativity (perhaps response related)
1300-2000 (2100-2800)	positive	Cz	a late positivity

* Contingent negative variation

** Post-imperative negative variation

These time windows are marked on a representative waveform from a single subject average in Figure 10.

Insert Figure 10 About Here

An analysis of variance was applied to all three measures (latency, peak amplitude, peak to peak amplitude), using a repeated measures design

(ALICE statistical package, Grubin, Bauer, & Walker, 1976).

Results and Discussion

The preliminary analyses revealed many differences between conditions, but not between groups. We will present group differences in a separate section below. Most of the interesting significant effects were on the P300 component of the ERP, and we will focus on this component here. (See Appendix A for a description of P300 and a discussion of its use in the study of information processing.) The amplitude differences below will refer to the baseline to peak measures, although the peak to peak measures usually gave identical results.

Grand average waveforms are presented in Figure 11. These waveforms represent the three conditions in the mixed blocks (see Figure 9), and are averaged over all 15 subjects and all five ERP sessions. All amplitudes and

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Insert Figure 11 About Here

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latency differences discussed below are significant at $P < .05$.

There was a large P300 elicited by the warning stimulus, followed by a CNV (contingent negative variation). CNVs are typically recorded in S1-S2 paradigms such as this one, with maximum negativity usually observed at the vertex (Cz) electrode. CNVs are observed when a subject must prepare for a perceptual or cognitive decision, or hold a motor response in readiness. The P300 was similar to a "classic" P300, with a maximum positivity at Pz and a minimum at Fz. This can be clearly seen in the single subject average of Figure 10. After the letter presentation another P300 was elicited,

followed by negative activity probably associated with response processes. In some subjects this negative activity was followed by very late positive activity toward the end of the epoch (see Figure 10).

P300 elicited by the warning stimulus

There were effects on both P300 latency and amplitude. The response to single left presentations elicited a smaller amplitude P300 than responses to either single right or dual presentations ($F(2,24) = 6.79$). The latency of P300 to single right presentations (mean = 531 msec) was longer than to either of the other two types (dual = 471, single left = 470) ($F(2,24) = 20.99$). These differences are clearly evident in Figure 11. We will discuss them in the General Discussion below. The largest CNV was elicited by the single right warning stimulus ($F(2,24) = 4.21$). Since the CNV is maximal at the Cz electrode site, this difference is not clearly evident in Figure 11, which presents averages at Pz.

P300 elicited by the letter presentation

There were significant effects on both P300 latency and amplitude (for latency, $F(2,24) = 7.61$; for amplitude, $F(2,24) = 16.06$). P300s elicited by dual letter presentations were much larger than those elicited by either single condition, as evident in the grand average waveforms in Figure 11. Since P300 is sensitive to the allocation of perceptual and central-processing resources (see Donchin, Kramer, & Wickens, in press), the larger P300 to dual presentations may reflect the greater difficulty of this condition, and the additional effort required.

P300 latency to single left presentations was faster than to single right (by an average of 56 msec), as is evident from Figure 11. However,

not evident in Figure 11 is the difference between duals and single left presentations. Latency to duals was approximately 40 msec faster than to single left presentations (means: duals = 573, single left = 613, single right = 669). The reason this difference is not evident in the grand average waveforms is probably due to a slight "smearing" of the P300 from latency variability over sessions and subjects.

To interpret these results we should first examine the relationship between P300 latency and reaction time for responding to the letter presentations (by depressing the appropriate key or keys). This is shown in Figure 12. As described above, RT to single left presentations are faster than to single right, and this difference is mirrored by differences in P300 latency. Our interpretation is that English speaking subjects have a

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Insert Figure 12 About Here

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tendency to learn the left hand codes first, and that it is these motor codes that are stored, along with a transformation rule for right hand codes. When a letter appears on the right, left letter codes must by accessed and a transformation performed before a response can be initiated. P300 latency reflects the completion of evaluation and decision processes. In this case P300 latency will reflect the time necessary for letter recognition and the subsequent choice of the appropriate letter code. Since an added step is required for letters presented on the right (the transformation from left hand codes), RT and P300 latency will be longer. Note that we will also be able to test this hypothesis in our study with Hebrew speaking subjects. These subjects, since they read from right to

left, should have a tendency to learn the right hand codes first, and so RT and P300 latency should be faster for the single right presentations. RT, we already know, is faster for single right presentations in Hebrew speaking subjects.

Since P300 latency has been shown to be independent of response-related processes (see Appendix A), and since there is a corresponding increase in both RT and P300 latency between single left and single right presentations (the lines are parallel in Figure 12), we conclude that the difference in RT is not due to processes related to response processing or execution.

For dual letter presentations there is an apparent dissociation between RT and P300 latency. RT is slower than both single presentation conditions, while P300 latency is faster. Our interpretation is that processing starts early in this condition, because it is the most difficult. Subjects know at the warning that a dual presentation will occur. Since this is the most difficult condition they begin allocating resources soon after the warning, and they are ready to begin processing more quickly after the letters appear than in either of the other two single letter conditions.

The RT in Figure 12 reflects the first of the two responses (the subject must respond to both letters), but the "savings" data presented above demonstrate that both letters are being processed in parallel to some extent. The interval between responses also indicates that both letters are being processed before the first response, because the response to the second letter sometimes follows the first by as little as 20 msec. RT for the first response is thus not an accurate measure of processing the first letter alone. Note that subjects were <u>not</u> instructed to respond to the left letter first, although this was in fact nearly always the case. They could

respond to either first, or both simultaneously. Had subjects been instructed in dual letter conditions to respond to the left letter as quickly as possible, it is likely that there would be less of a discrepancy between RT and P300 latency. In such a situation it would be very interesting to examine the extent to which the RT to the first response was still delayed; presumably, such a delay would mean that the subject was unable to stop simultaneously processing the other letter. Another way to phrase this question is to ask, to what extent is the simultaneous processing of both letters automatic?

We should reemphasize several points here. First, although all the subjects were right handed, the RT to single left presentations was faster than to single right. Note that the warning provides information as to where the letter will appear. For both single presentations the subject should be focusing on the exact spot where the letter is about to appear. Even so, left RTs are faster than right RTs. In Isreal, with right handed subjects who read from right to left, the results were reversed, with RT faster to single letter presentations on the right.

One might expect the differences between left and right presentation to disappear over time, as automaticity developed. This happened with neither RT or P300 latency, as there was no change in the relationship between left and right over the five ERP sessions.

Group differences in "Conflict" conditions

As described above, in the dual limited condition all trials involved dual letter presentations, and only a limited set of eight letters was used. When the same letter was presented on both sides we classified the trial as

either "conflict" or "no conflict," depending on whether or not the hand symmetry and spatial conditions differed. With letters that require key presses symmetrical around the center, left responses in both groups will be identical (there will be no conflict between the groups). This is the case for the letters E, N, H, and S, as depicted in Figure 13. For letters that are not symmetrical there will be conflict between the groups, because the left hand responses will differ, reflecting either a spatial or hand symmetrical transformation from the right to the left hand. (Remember - in all groups the right hand responses are identical.) In the dual blocks this

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Insert Figure 13 About Here

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happened for the letters I, A, T, and U.

Our hypothesis is that there is a tendency for simultaneous activation of symmetrical fingers. This is depicted in Figure 14, where the Xs over the right hand keys represent activation produced by the key presses of the symmetrical fingers on the left hand. This conflict should lead to a

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Insert Figure 14 About Here

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response superiority for hand symmetry in the conflict condition, because in this condition the same letter is presented on both sides, and the activation of corresponding fingers will aid processing. When considering, a priori, the comparative difficulty of the hand symmetry and spatial conditions most people think initially of this situation - dual presentations of identical letters, and therefore judge the difficulty

inaccurately, for in our paradigm this situation is comparatively rare. When the same letters are presented to both sides, but different fingers must be used (spatial condition), then the tendency for the same fingers to be activated will interfere with response execution and RT will be slower.

The RT and P300 latencies for the conflict conditions are shown in Figure 15. (Cross conflict and cross noconflict will not be discussed in this report.) As predicted, and discussed above (see Figure 6), the only instance in which the hand symmetry condition is faster than the spatial condition is during conflict trials. P300 latency, however, does not vary,

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Insert Figure 15 About Here

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confirming our hypothesis that the locus of this effect is not at the level of stimulus evaluation or categorization, but rather at the level of motor programming and execution.

The difference between the hand symmetry and spatial groups in their response to conflict versus no conflict trials is very nicely represented in the ERPs in the form of a late negativity that is most likely response related. On the left side of Figure 16 ERPs from the early (first two) and late (last three) sessions of the hand symmetry group are presented, while the spatial group is on the right. There are large differences between

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Insert Figure 16 About Here

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groups in the negativity that develops about 500 msec after the letter presentations, and continues throughout the epoch. In the hand symmetry

group this negativity is greater for the no conflict condition, while this is reversed for the spatial group, where the negativity is larger for the conflict condition. In the combined group there were no ERP differences between conflict and no conflict conditions.

GENERAL DISCUSSION

There are two focal points to the interpretation of the present results. One is the emerging structure and internal mechanisms of the skill developed on the new chord keyboard. The other is the influence on performance of different coding principles. We begin with a discussion of the first topic and continue to examine the representation issue.

In the task of transcription, when series of semantic messages have to be transcribed into trains of motor productions, differences between conditions in response times and errors are interpreted to indicate additional work, bottlenecks in processing, or reduced efficiency of the system. One way to generate and test hypotheses on the causes of such differences is by examining the consequences to performance of systematic manipulations of independent variables. A converging source of information is the analysis of the accompanying electrophysiological activity of the brain. ERP measures can provide important, and to a large extent independent, clues to a decomposition of processing and response activity on the path from stimulus to response.

Average entry times of letters in the present experiment varied considerably between the different types of experimental trials. Single letter trials were faster than dual letter trials. Left hand entries were

faster than right. Entry times of pairs of the same letters were faster than those comprising two different letters. Practice had a strong main effect on response time, and in addition interacted with all other variables. The accompanying analysis of event related brain activity showed that in each trial a distinct segment could be associated with processing and preparation activity following the warning signal. A second epoch was connected to the actual presentation of letters. A third segment appeared at a later stage, close to or following the response. Within each of these segments, a distinction was made between ERP activity manifested in the P300 component (Appendix A), which is likely to be related to encoding and central processing operations, and activation tied to motor related processes. Components associated with motor processes are revealed in late negativities. They usually show the largest peak on the electrodes contralateral to the operating hand, or on the Cz electrode of the midline positions. Similar to the behavioral measures, comparison among types of trials revealed differences in ERP averages between single and dual letter trials, and between typing hands. In contrast to the strong effects that were observed in response time measures, most ERP measures were not sensitive to the effect of practice, and to differences in typing same and different pairs of letters. What can be learned from the joint pattern of behavioral and ERP results on the requirements of typing on the chord keyboard?

The difference between single left and right trials appeared not only in response times but also in the ERP activity. It is interesting that differences in ERPs were already observed following the warning signal on the arrival and type of trial. They were manifested both in the latency and

amplitude of the P300. It is clear that a warning on a right hand trial was perceived and prepared for differently. Our interpretations of these differences is as follows. Subjects read from left to right, and have a preference to scan from left to right. They are, in a sense, "primed", or more prepared, for stimuli to appear on the left. Both duals and single left presentations contain a warning dot on the left, and latencies for these two conditions are equal. In the third of the trials that contain only a single right warning dot, stimulus evaluation is delayed, and P300 is longer in this condition (on an average of 60 msec). Because single right presentations are unexpected, more preparation will be required prior to the letter presentation, and this explains why the largest CNV is elicited by the single right warning stimulus. Note that on two-thirds of the trials subjects will be correct in expecting a left warning dot to appear. This leads to the differences in amplitude, since right presentations, being rarer than presentations that contain a warning dot on the left, will elicit a large P300. The effect of probability on P300 amplitude is one of the most consistent ERP findings (see, for example, Duncan-Johnson & Donchin, 1977). As probability decreases, amplitude increases. Although less well documented, it has also been frequently reported that rare stimuli also elicit a P300 with a longer latency than comparable frequent stimuli.

The warning for duals also elicits a large P300. This may occur because subjects know that the task of responding to the dual letter presentations (that will soon appear) is very difficult. The P300 elicited by the warning may thus represent the marshalling of processing resources for the difficult task to come. Warnings for single left presentations elicit small P300s because a left warning signal is expected, and the

upcoming task will not be a difficult one.

Recall that differences between hands in single letter trials were also found in the latency and amplitude of the P300 following the actual presentation of the letters. Such differences cannot be attributed to differential expectations or preparatory activity, because the long foreperiod gave subjects enough time to prepare. Two alternative interpretations can be offered for these effects. One is that our English speaking subjects, due to their reading habits, tended to begin with, emphasize more, and master first, the left hand set of codes. Consequently, they had more difficulties in processing and retrieving the codes for right hand letters. An alternative, and more intriguing possibility is that in our task, subjects committed only one set of codes to memory together with a transformation rule. Again, due to their biases, they preferred to learn the code for the left hand, and in addition a transition rule from left to right hand production. As a result, when a left hand letter was presented its code was accessed directly, while an additional step was required when a right hand letter was presented, leading to a prolonged latency and more intensive processing efforts. The single store idea is supported to a certain extent by informal reports of subjects describing their mnemonics during the acquisition of codes. Based upon the present results both interpretations are speculative and cannot be distinguished from each other. If they are correct, reversal of trends should be observed for Hebrew speaking subjects, and for subjects trained solely on the right hand panel before transferring to a left hand operation. Both types of information are presently being collected.

To summarize this section, we can say that the joint ERP and behavioral analysis showed that the differences between right and left cannot be attributed to the influence of a simple motor or response related factor. The analysis of ERP data has specified the existence of at least two loci in the encoding and central processing activity that may well be the sources of the observed differences in response times.

An additional interesting and potentially important result from the ERP analysis is the shorter latency of the P300 component to the presentation of letters in dual letter trials. Dual letter trials by their nature can be argued to impose greater processing and response demands on the performer relative to single trials. The difference in demands was reflected in the substantial increase of response times and errors in dual letter trials. The ERP data showed that differences between single and dual letter trials were already present in the preparation stage following a warning signal, generally indicating more intensive efforts to recruit resources. Also consistent with the additional processing requirements was the increase in amplitude of the P300 component following the presentation of the letters in dual compared with single letter trials. An apparently inconsistent finding was the shorter latency of this P300 component relative to single letter trials. However, upon second consideration, this outcome may not be inconsistent, but reflect an additional effort to recruit resources on the part of the performer. If the latency measure of an ERP component is taken to indicate the time at which a respective process has begun, and the amplitude is an indication of its intensity, we can deduce that in dual letter trials the process that is represented by the P300 component started earlier and reached a higher intensity. This is in addition to the fact

that a more intense preparation activity was observed following the warning signal.

In dual letter trials it is as though the processing system attempted, and succeeded, in recruiting more resources at an earlier time to meet the increased demands of typing two simultaneous letters. The observed deficits in performance can thus be interpreted to occur despite the additional effort, and thus to reflect inability or failure of the attempt to recruit all the additional resources needed to meet task demands within the same unit of time that was observed for single letter trials. Several authors have suggested that we view the supply of processing facilities to the performance of tasks as an integral of recruitment rate over time (e.g., Navon & Gopher, 1979; Norman & Bobrow, 1975). Given the demonstrated relationship between latency and amplitude of P300 and processing efforts, the present findings are an important observation that underlines the fact that there may not be a direct correspondence between decrements in performance and the amount of additional effort required, and made by the system to meet task demands. Using only the conventional measurement approach, based solely upon interpretation of decrements in performance, it is impossible to estimate how far the system is from its capacity for additional work before the first decrement in performance is measured. Only with the employment of a second and converging measurement technique, can we hope to develop a satisfactory evaluation methodology for the additional costs to the processing system of increased task difficulty.

In light of the above argument, we should not ignore the absence in the ERP measures of practice effects, and the differences between typing same and different letters by the two hands. It is as though the timing and

intensity of the central processes that are reflected in the ERP were not changed with the advance of training, and with the typing of same and different letters. How can this outcome coexist with the substantial differences in the latency of responses that was found in both of these cases. One possible interpretation is that the improvement of performance with practice was due to processes that were not reflected at all in the ERP measures. A more tempting possibility, that is also more consistent with our view of resources, is that the efficiency of the stimulus response loop was increased without changing its nature. That is, the same internal mechanisms and processes were tapped and worked at the same, or possibly higher, intensity. However, the quality of their output was improved and the amount of work completed in a given unit of time was larger, leading to an earlier triggering of overt responses with improved accuracy. For example, as training progressed there was an improvement in the work related to feature extraction, the identification of letters and the retrieval of their codes, and the signal to noise power of muscle commands. At this time we do not have enough information to favor or specify one of the two interpretations. They hint again at the importance of studying the time/intensity tradeoff of processes deployed by the human processing system to meet task demands.

We now turn to consider the specific effects of the three representation rules. Coding principles had a pronounced influence on performance efficiency and its impact increased with the progress of training. Coding by hand symmetry led to the lowest levels of performance. Representation by spatial arrangement had an intermediate level. The combination of the two in a vertical posture was most beneficial to

performance. This order of groups in performance efficiency was revealed in all conditions and on all measures, but was clearest and most pronounced in dual entry trials, when retrieval and execution of two simultaneous chords was required. The only exception to this order were trials of typing the same letters on both panels. Here the hand symmetry group outperformed the spatial group. Recall that subjects using spatial arrangement as a coding principle were required to use different fingers to type the same letter on the two panels, while subjects in the hand symmetry group were required to press different key patterns but used the same fingers. This single instance of reversal in efficiency may give us the clue to the superiority of the spatial arrangement principle in all other conditions.

A closer examination of the differences between the Hand Symmetry and the Spatial arrangement groups lead us to believe that the cause of their differential efficiency may not be the superiority of the spatial arrangement principle as such, but a situational disadvantage of the hand symmetry principle for the performance of the present task. This is a two step argument. One step is an assumption that due to the anatomical structure, or the functional relationship between hands, or both, whenever a combination of fingers of one hand are activated (for example, while typing a letter chord), the symmetrical fingers of the other hand are also automatically primed, or increase their activation. There is some evidence from behavioral research to support this assumption. Studies of reaction times, using single fingers of both hands to respond in choice reaction tasks, showed that successive response times made by a symmetrical finger of the other hand were faster than those requiring the operation of an asymmetrical finger (Rabbitt, Vejas, & Fearnley, 1975). To our knowledge,

direct physiological research has not been conducted to test this hypothesis. Additional evidence in support of the argument may be the differences found in the ERP records of the HS and SPA groups in the typing of conflicting and nonconflicting pairs of the same letters. For both groups, differences between the two types of trials appeared as motor related activity and not in encoding or central processing activity, hence favoring a motor related locus in the base of the response time differences between these types of trials. The activity for the HS group was more intense in the group of the more difficult motor chords (the no conflict letter group). Activity for the SPA subjects was larger when they were required to operate simultaneously different fingers for entering the same letters (the conflict letter group), reflecting the worst case of required inhibition of spontaneous symmetrical activation. We reiterate the significance, for the support of the symmetric activation hypotheses, of the fact that differences were found only on components related to late motor activity.

The second step in the interpretation of the HS inferior performance, relates the priming assumption to the conditions in which the differences between groups were maximal, namely, response times in dual letter trials. Given that all 26 letters were used with equal probabilities, there were 676 dual letter combinations, only 26 of which were composed of the same letters on both panels. Therefore, on approximately 96% of dual trials (in mixed blocks) two different letters were presented. Subjects almost always responded to the left letter first. Activation of a left hand chord would also cause the spontaneous activation of the symmetrical fingers of the right hand, which would have to be inhibited, because a chord combination

corresponding to a different letter had to be generated. The situation is depicted in the hypothetical examples plotted in Figure 14.

In this situation subjects trained under the spatial arrangement rule had an advantage because they were taught to always ignore and inhibit all information resulting from hand symmetry considerations and only depend on the pattern created by keys. In contrast, the hand symmetry group was put under a continuous conflict. On the one hand they had to inhibit the spontaneous activation due to hand symmetry, on the other hand they had to refer to hand symmetry in order to memorize the codes of the letter they were required to type. This creates a double bind, and use of the hand symmetry principle may thus lead to confusions and conflicts, and slow down responses. The power of this conflict may even be larger if the single storage hypothesis is supported. That is, we assume that subjects memorize only one set of letter codes and a transition rule to codes of the other hand. The only time in which the conflict for the HS subjects was resolved was when the same letters had to be typed on both panels (bottom row, Figure 14). These were indeed the trials in which hand symmetry subjects had the least problems.

Representation by spatial patterns, anchored in an objective and external reference point, appears to be a better coping strategy with the requirement to coordinate the work of the two hands when typing different chords. But, it was not the best. A resolution of both representation conflicts in the vertical posture led to best performance. Also, as the data show, subjects trained under the spatial arrangement principle were more susceptible to errors due to confusions between patterns, and had the aforementioned disadvantage in typing same but conflicting letters. It

appears that both types of incompatibilities are decremental to performance, possibly because both principles are well rooted and long experienced mediators of intentions and actions. Performance benefits most from resolving both. Note that here again we prefer, at this time, an interpretation in terms of reduced incompatibility, and not as a result of an advantage for an inherent, natural representation principle. Note also that the advantage of the combined group was attributed to their improved representation rule. There is also the possibility that it may stem from biomechanical reasons, due to a better ability to coordinate the hands in vertical compared to horizontal condition. Additional experiments conducted in our laboratory to test this issue provided a clear support to the representation interpretation (Gopher, Karis, & Koenig, in preparation).

The effects on performance of the three representation principles are not only interesting in view of the observed differences between groups, but should be considered from a more general perspective of the acquired psychomotor skill. The magnitude of the differences between groups attest to the crucial role of high level representations in the acquisition and operation of complex motor skills. Moreover, the increase of the difference with the progress of training suggest that the influence of representation modes are not a transient phenomena of early training, but an important determinant of the efficiency of skilled movements. Two specific arguments that can be made based upon these findings, other than the general power of the experimental manipulation, concern the selection of representation mode and the determinants of improvement with training. From the fact that subjects did not object or reveal a major problem in concurring with any of the three coding rules, it can be deduced that the human processing system

has the strategic freedom to adopt different representation modes. At the same time, the fact that performance in the three groups did not converge with prolonged practice indicates that once a representation rule has been adopted it is likely to persist. There was no evidence in the present data for the existence of a "natural", dominant and powerful representation mode that would ultimately take over, even if at an early stage of training subjects had a different starting point (representation rule). Development of a common representation mode implies a convergence between groups in their performance levels as a function of time on task, which was not observed. Similar observations on role of high level representation of motor plans were made in an earlier study, experimenting with a different type of a chord keyboard (Gopher, 1984).

Another conclusion prompted by the present results is that with the advance of training, skilled transcription cannot be argued to become more motor or peripherally controlled, in the common usage of these concepts within human performance theory. If the coding rules are hypothesized to influence the nature of the representation of action plan in long-term memory, and the influence of such rules increases with practice, the conclusion that high level representations are a part of the stimulus response loop of a skilled response is inevitable. The observed marked increase in performance efficiency with the acquisition of skill cannot, therefore, be attributed to a reduced dependence on high level representations and to the creation of a direct and independent link between stimulus to response that does not include them. An establishment of such links, bypassing the upper, abstract levels of the central system, has been for many years the prevalent view on the transition in the organization of

skills with training (Fitts & Posner, 1967; Welford, 1976). Current views on skill acquisition emphasize the role of well organized schemas of action plans that are activated automatically, but say very little on the nature and structure of such schemas (e.g., Norman & Shallice, 1981; Schmidt, 1975; Schneider, 1983). Our findings are consistent with these views and contribute to their clarification. They show that action schemas are not constructed in a single uniform way. They can vary qualitatively and have different vantage points.

Appendix A

Cognitive Psychophysiology

Cognitive Psychophysiology, as its name implies, is a marriage of cognitive psychology and psychophysiology. The basic premise of this union is that the understanding of cognitive processes can be enhanced by augmenting the traditional tools of the cognitive psychologist by adding tools based on the measurement of physiological functions (Donchin, in press). The psychophysiological data are, of course, useful only to the extent that they complement and expand the view of the mind that can be developed with the use of more traditional techniques.

Psychophysiologists are psychologists who extend the range of observable aspects of behavior by developing, and using, techniques that allow the measurement of the activities of "physiological" systems. The reference is generally to the measurement of such variables as Heart Rate, the Galvanic Skin Response or the Event-Related Brain Potential (ERP). When such measures are described as "physiological", and this term is used to distinguish these recordings from "behavioral" measures, one espouses a model that implies a separation between "behavior" and "physiology" that is not easily supportable. It seems better to adopt a holistic view which maintains that the organism in its entirety is involved in any act. Although action is ultimately manifested by specific muscular acts, a description of these acts is not an exhaustive (or even a sufficient) description of behavior. It is clearly the case that vascular, glandular, and neural activity are part and parcel of the same behavioral act. For

example, when a person utters a sentence, a transcription of the sentence may for certain purposes be a sufficient record of the speech act. But changes in cortical blood flow that accompanied the utterance may well be a necessary component of the speech act, and therefore, these blood flow changes are as much "behavior" as are the utterances. The psychophysiologist expands the study of behavior by including measures of these internal activities in the range of observation. In this fashion, it is possible to monitor behavioral subsystems whose activity cannot be observed when one restricts measurement to overt (muscular) behavior. In this way the psychophysiological enterprise, when properly deployed, enriches the study of cognition.

The range of internal, "physiological" processes which can be measured is large. In fact, any physiological function that can be measured from the human without puncturing the skin qualifies as a psychophysiological measure.

The Event-Related Brain Potential

The ERP is a series of voltage oscillations that are time-locked to an event. It is derived by averaging samples (epochs) of the electroencephalogram (EEG) recorded from the human scalp with each sample having the same temporal relationship to a particular event. Note that we can look at activity preceding an event, as well as activity following an event. This is particularly important in investigations of preparatory processes. The voltage oscillations derived in this manner are regarded as manifestations of different "components". Components are defined in terms of their polarity (positive or negative voltage), latency range (temporal

relationship to the event), and scalp distribution (variation in voltage with electrode location on the scalp), as well as by their relationship to experimental variables. Components can be quantified using simple magnitude measures or through the application of more advanced techniques such as Principal Component Analysis (PCA) and Vector Analysis (Gratton, Coles, & Donchin, 1983). They are labeled by a polarity descriptor (P or N for positive or negative) and a modal latency descriptor (e.g. 300, for 300 msec). Thus, the P300 is a positive ERP component with a modal latency of 300 msec. In some cases, as with Contingent Negative Variation (CNV) and Slow Wave (SW), the descriptors are omitted.

The Psychophysiological Paradigm

The assumptions and the model underlying the use of ERPs by the Cognitive Psychophysiology Laboratory have been presented elsewhere (Donchin, 1979, 1981). In brief, we assume that the voltages we record at the scalp are the result of synchronous activation of neuronal ensembles whose geometry allows their individual fields to summate to a field whose strength can affect scalp electrodes (Galambos & Hillyard, 1981). It is convenient to parse the ERP into a set of components. The component, in our scheme of things, is characterized by a consistent response to experimental manipulations (see Donchin, Ritter & McCallum, 1978, for a discussion of components). We further assume that each component is a manifestation at the scalp of an intracranial processing entity. We are not implying that each ERP component corresponds to a specific neuroanatomical entity or that the activity manifested by the component corresponds to a distinct neural process. Rather, we assume that a consistent information processing need,

characterized by its eliciting conditions, activates a collection of processes that, for perhaps entirely fortuitous reasons, have the biophysical properties that generate the scalp-recorded activity.

As a working hypothesis we postulate that ERP components are manifestations of functional processing entities that play distinct roles in the algorithmic structure of the information processing system. In other words, we believe that it is possible to describe in detail the transformations that the processing entity applies to the information stream. The goal of Cognitive Psychophysiology, within this framework, is to provide such detailed descriptions. This may be achieved by developing comprehensive descriptions of the conditions governing the elicitation and attributes of the components (the "antecedent" conditions). These descriptions can be used to support theories that attribute certain functions to the subroutine manifested by the component. In turn, the theories should lead to predictions regarding the consequences of the elicitation of the subroutines, predictions that can be tested empirically. The P300 component of the ERP has been analyzed in this manner in some detail, (see Donchin, 1981, for a discussion of the general approach; and Karis, Fabiani, & Donchin, 1984, for an illustration of an empirical test of a prediction regarding an ERP's consequences).

Overview of Early Work

P300 and Subjective Probability

The P300 is often recorded in the so-called "oddball" paradigm. The subject is presented with two stimuli, one rare and one frequent, that occur in a Bernoulli sequence (i.e., on any given trial one of two stimuli can

occur and their probability is complementary), and is instructed to keep a mental count of the rare stimulus. Consider, for example, the study by Johnson and Donchin (1982), who presented the subject with a sequence of tones of two different frequencies, 33% of which were of one frequency and 66% of the other frequency. Furthermore, every 40 to 80 trials the probability of the stimulus was reversed, unbeknownst to the subject. The subject was instructed to count the number of times the low pitched tone was presented. Presentation of the rare tone elicited a large, positive-going ERP whose peak amplitude occurred approximately 300 msec after the tone, the P300. Thus the rare, counted stimulus produced a large P300. It was of particular interest in this study that when the probabilities were reversed, the larger P300 was elicited by the rarer of the two tones, rather than by the counted tone. Thus, one or the other of the two stimuli elicited the large P300 in different segments of the series. It should be noted that even though probability appeared to be the prime factor controlling P300 amplitude, the counted stimulus, when rare, elicited a larger P300 than was elicited by the uncounted stimulus when it was rare. This "target" effect points out that the amplitude of P300 depends on (i) the probability of occurrence of a stimulus and on (ii) the task relevance of that stimulus.

This dual effect on P300 amplitude appeared in the first report of P300 by Sutton and his colleagues (Sutton, Braren, & Zubin, 1965) in a similar paradigm. Since this initial report, the P300 has been observed in a wide variety of different circumstances (Pritchard, 1981). The diversity of the conditions in which this component can be elicited are, however, all variants of what is known as the "oddball" paradigm. There is typically a sequence of two stimuli, presented every 1 to 2 seconds, that appear with

unequal probability. The subject is assigned a task which requires that the stimuli be processed. Almost invariably, the rare stimulus elicits a P300. That the ERP elicited across the various oddball tasks is a P300 is implied by the observation that the scalp distribution of the component is largely invariant; it is largest at the parietal electrode, somewhat smaller at the central electrode, and virtually nonexistent at the frontal electrode.

Although the early work by Sutton's group demonstrated that probability is an important variable in determining the amplitude of P300, it was not quite clear if the critical aspect of this variable was the objective, prior, probability of the stimulus events or their subjective probability as determined by the subject's perception of the situation. The manner in which this issue was addressed is illustrative of the approach taken to resolve issues within the cognitive psychophysiological paradigm. The challenge posed by the paradigm is that first we elucidate the antecedent conditions for the elicitation of P300. These conditions must be described with as much precision as possible. Thus, knowing the variables that actually control P300 is crucial. Determining, in each case, the variables that control the P300 dictates a choice between quite different models of the component. For example, if the amplitude of the P300 is controlled by the prior probability of a stimulus, determined solely by the environment in which the stimulus is triggered, then the subroutine that we seek must be lodged in the periphery, controlled more by the nature of the physical stimuli than by the structure of the psychological situation in which they are embedded. If, on the other hand, the subjective probability is critical, then we are probably observing quite a different class of subroutines, anchored in deeper levels of psychological processing.

Subjective probability was demonstrated to be the crucial variable in a series of experiments conducted in this laboratory (see for example, K. C. Squires, Wickens, N. K. Squires and Donchin, 1976), who showed that ERPs were elicited by the same physical stimulus, and this stimulus had the same objective prior probability throughout, namely, 0.5. The subject's task was to count the number of times one of two tones of different frequencies was presented. Experimental trials were sorted so that in one group the counted tones were preceded by uncounted tones, while in another group counted tones were preceded by other counted tones. By sorting trials in this way, Squires et al. were able to show that a larger P300 was produced when the preceding stimulus differed from the counted stimulus. The longer the sequence of different stimuli that preceded the counted stimulus, the larger the P300 that was elicited by that stimulus. The longer the sequence of similar stimuli (i.e., those that were also counted) preceding a counted stimulus, the smaller the P300 elicited by that stimulus. Thus, there is an exquisitely sensitive relationship between the precise structure of the sequence preceding a stimulus and the amplitude of the P300 that it elicits.

P300 and Stimulus Evaluation

The data reviewed above suggest that P300 manifests a "subroutine" that is invoked whenever task relevant, novel, events occur. The relation between P300 and the Sokolovian mismatch detector follows logically from these data. If the P300 is a manifestation of the activation of a mismatch detector (or of a consequence of such activation) then its latency should be strongly related to the detection of the mismatch and therefore, P300

latency should be positively correlated with Reaction Time (RT). This, as reviewed elsewhere (Donchin, 1981) is not the case. The evidence is strong that P300 latency may be either shorter or longer, or equal to the RT. We proposed the hypothesis that P300 is invoked after the event has been categorized to an extent greater than is necessary for the generation of some overt responses. Thus, the specific response made on any given trial may not depend on P300. Rather, the P300 manifests a process whose function pertains to future, rather than to present, actions. This hypothesis implies that variables that affect perceptual processing speed and categorization time should affect the latency of the P300 component. This prediction was confirmed in two studies from this laboratory which have shown a relationship between P300 latency and stimulus evaluation processes.

Kutas, McCarthy, and Donchin (1977) used a choice RT task in which subjects were instructed to either respond accurately or quickly in different experimental runs. Under accuracy instructions, RT and P300 were significantly correlated and RT usually followed the P300 on individual trials. Under speed instructions, the RT-P300 correlation was low and non-significant. Also, the RT often preceded the P300 on error trials. These data support the hypothesis that P300 latency is a real-time index of the stimulus evaluation process. Under accuracy instructions, subjects must wait until the stimulus evaluation is at least partially completed before responding. Therefore, RT and P300 latency are correlated. Under speed instructions, subjects will often respond before sufficient stimulus evaluation has taken place and RT will precede P300 latency.

An additional comparison of P300 latency and RT was performed by McCarthy and Donchin (1981). If P300 latency is related to stimulus evaluation time, but is independent of response selection and execution time then it should be possible to dissociate RT and P300 latency by varying the compatibility of the stimulus-response mapping. In this study, a matrix of characters (4 rows by 6 columns) was presented on a visual display for 400 msec. Subjects were required to identify the target words "RIGHT" or "LEFT" embedded in the matrix by pushing a button. Target discriminability was manipulated by including the # character (no noise condition) or random alphabetic characters (noise condition) in the matrix. The compatibility of the S-R mapping was varied by presenting a cue word ("SAME" or "OPPOSITE") before the matrix. The cue word indicated whether a compatible or incompatible mapping of target word onto response hand was to be used. Both target discriminability and S-R mapping affected RT as expected. RTs were longer on opposite compared to same trials, and longer on noise compared to no noise trials. P300 latency however, was only affected by target discriminability, the noise condition producing a longer latency than the no-noise condition. These data provide strong support for the hypothesis that P300 latency can serve as a measure of stimulus evaluation time and is relatively independent of processes related to response selection and execution. These, and similar data from other laboratories, constrain models of the P300 subroutine to assume that its function is not related to the subject's immediate response to an event, as the response may precede P300 by hundreds of msec.

The Dual Task Problem

We now examine in some detail the role of task relevance in controlling P300 amplitude, as this set of relationships provides the basis for the primary use of the P300 as a tool in human engineering. It is noteworthy that the P300 is invoked only if stimuli are associated with a task that requires that they be processed. Ignored stimuli do not elicit a P300. What if the stimuli are only partially ignored? What if the subject is instructed to perform the oddball task concurrently with another task? Would the amplitude of the P300 reflect the centrality of the oddball task? Would it, perhaps, change with the amount of resources allocated to the oddball task? Clearly, if so the P300 may serve as a very useful measure of the amount of resources demanded by the two tasks. It is this series of questions that lie at the core of the usage that can be made of the P300 in the assessment of workload.

The study of cognitive workload and the allocation of processing resources to several tasks performed concurrently is, in fact, the area of research that has profited from the incorporation of ERP measures. The research reviewed here began in the Cognitive Psychophysiology Laboratory in the mid 1970's with the support from AFOSR. It has been performed within the framework of Resource Allocation theory. This class of models suggests that it is useful to conceptualize human capacity as represented by a finite pool of "resources" available for sharing among concurrently performed tasks (Kahneman, 1973; Moray, 1967; Norman and Bobrow, 1975). In the Kahneman (1973) model these processing resources were undifferentiated, implying that all tasks draw resources from the same pool. The model predicts that when two tasks are timeshared their performance should decrease relative to

single task levels.

The undifferentiated resource model underlies the secondary task technique, a method which is commonly employed in the assessment of workload (Knowles, 1963; Rolfe, 1971; Wickens, 1979). In the secondary task technique a subject is assigned two tasks; a "primary" task that is to be performed as well as possible and a second task that need be performed only to the extent that the primary task performance remains stable. It is assumed that the demands imposed upon the subject by the primary task can be assessed by monitoring performance on the secondary task. An easy primary task will require a minimal amount of processing resources, leaving an ample supply for the performance of the secondary task, while a difficult primary task will require the majority of processing resources leaving an insufficient supply for the performance of the secondary task. Thus, the better the performance of the secondary task the less demanding the primary task.

Although the secondary task procedure has been extensively used it presents a number of practical problems (Brown, 1978; Ogden, Levine and Eisner, 1979). Particularly unfortunate is the fact that the secondary task responses often intrude upon primary task performance. Fluctuations in primary task performance caused by the intrusion of the secondary task make interpretation of the resource trade-off extremely difficult. Evidently, it would be useful to have a secondary task which is sensitive to changes in primary task difficulty but which does not require an overt response.

The P300 as an Index of Cognitive Workload

We assumed that the oddball task can be used as a non-intrusive secondary task since ERP eliciting tones occur intermittently, are easily discriminable and do not require an overt response. Another advantage of this procedure is that it could be applied uniformly across different operational settings. In other words, the oddball task could be inserted into virtually any operational setting without requiring modifications in the system associated with the primary task.

In our experiments, the subjects sat in front of a CRT and were instructed to cancel computer generated movements by keeping a cursor superimposed on a target in the center of the display. This was acomplished by the movement of a joystick mounted on the right hand side of the subject's chair. Levels of tracking difficulty were manipulated by requiring the subject to track in either one or two dimensions (horizontal and/or vertical; Wickens, Isreal and Donchin, 1977). The compensatory tracking task was defined as the primary task. In addition to the tracking, the subjects were also instructed to count one of two tones presented in a Bernoulli series of high and low pitched tones. Control conditions were also included in which the subjects performed each of the two tasks separately.

The data indicate that the introduction of the tracking task drastically diminishes the amplitude of the P300. However, no further reduction in P300 amplitude could be observed as tracking difficulty was increased by requiring tracking in two dimensions. Tracking difficulty, as measured by root mean square error (RMS) and reaction time to probes, did increase with the addition of the second dimension. Isreal, Chesney, Wickens

and Donchin (1980) conducted a similar study requiring subjects to perform a compensatory tracking task concurrently with a counting task. In this case, however, the bandwidth of the random forcing function rather than the dimensionality of the tracking task was manipulated. The bandwidth was increased gradually until the cursor's speed reached the highest level the subject could tolerate without exceeding a preset error criterion.

The results showed that P300 is diminished by the introduction of the tracking task. However, increases in the bandwidth of the forcing function did not produce systematic changes in the amplitude of the P300 elicited by the counted tones. These results cannot be explained easily within the framework of an undifferentiated capacity theory if we assume that P300 amplitude indexes the demands placed upon the subject by the primary task. Increasing the bandwidth clearly affects the performance of overt secondary tasks (McDonald, 1973; Wierwille, Gutmann, Hicks and Muto, 1977). The fact that P300 did not change, even though a dramatic drop in amplitude was observed with the introduction of the tracking task, required explanation.

A possible interpretation of these data is that the resources that are tapped when the dimensionality, or the bandwidth of the tracking task are increased may not be the same as the resources required by the oddball task. Several investigators have proposed that processing resources are not undifferentiated but are structured according to various information processing stages (Kantowitz and Knight, 1976; Kinsbourne and Hicks, 1978; Navon and Gopher, 1979; Sanders, 1979). One such model proposed by Wickens (1980) has identified hypothetical processing structures on the basis of input and output modalities (visual-auditory, manual-vocal), stages of information processing (encoding and central processing, response selection

and execution) and codes of processing (verbal and spatial). In this framework dual-tasks are expected to interfere to the extent that they share overlapping resources. For example, two tasks which both require substantial perceptual processing will interfere with each other to a greater extent than one task which requires perceptual processing and another task with heavy demands for response related resources. This view of the allocation of processing resources is consistent with studies which show little or no decrement in performance when two difficult tasks are time-shared (Allport, Antonis and Reynolds, 1972; North, 1977; Wickens and Kessel, 1979).

Isreal, Wickens, Chesney and Donchin (1980) tested this hypothesis by combining the oddball task as a secondary task with a visual monitoring task that served as the primary task. The subjects were instructed to monitor a simulated air traffic control display either for course changes or for intensifications of one of two classes of stimuli (squares or triangles). Primary task difficulty was manipulated by increasing the number of elements traversing the CRT (Sperandio, 1978). The number of targets on the screen did have a systematic effect on reaction time to the tones when subjects were monitoring for course changes. Reaction time increased monotonically from the control condition to the condition in which subjects were required to monitor eight elements simultaneously. However, in the flash detection condition reaction time did not increase significantly as a function of the number of elements displayed.

The P300 elicited by the counted tones showed a monotonic decrease with increases in the difficulty of the monitoring task when subjects were detecting course changes. In the flash detection condition P300s decreased

with the introduction of the monitoring task, but increases in the number of display elements failed to further attenuate P300 amplitude. Thus, in this experiment the P300 findings were consistent with the reaction time data. It appears that since the primary task did not require a response, P300 amplitude was sensitive to the perceptual/cognitive demands of a task while being relatively uninfluenced by response related demands. Thus, both the amplitude and latency of the P300 component seem sensitive to a subset of processes which are reflected by more traditional measures of human performance such as reaction time This selective sensitivity of the P300 component makes it a particularly useful workload metric. The use of traditional measures of task difficulty such as reaction time and root mean square tracking error in conjunction with P300 permits the decomposition of the resource requirements of dual-tasks.

Appendix B

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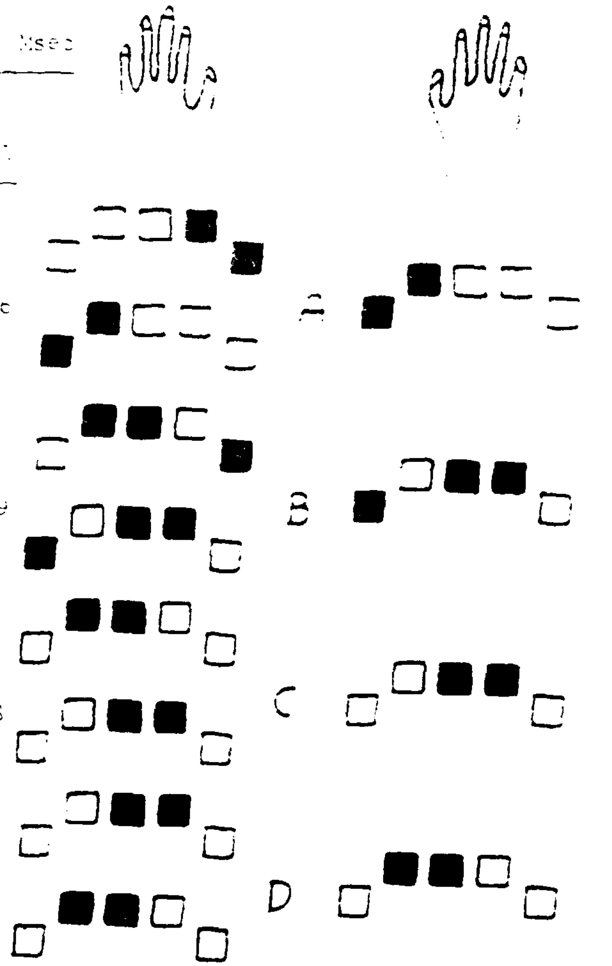

Condition	Single letter trials (Msec) HS	[illegible]	[illegible]	Dual letter trials (Msec) HS	[illegible]	[illegible]	Single letter trials (Msec) HS	[illegible]	[illegible]	Dual letter trials (Msec) HS	SPA	CPY
A	[illegible]	[illegible]	452	762	717	646	553	523	55[illegible]	1044	936	95[illegible]
B	633	817	609	904	960	769	802	839	662	1149	1114	101[illegible]
C	794	542	531	915	773	728	664	627	620	114[illegible]	1053	97[illegible]
D	712	686	510	930	757	761	662	595	645	1116	981	935

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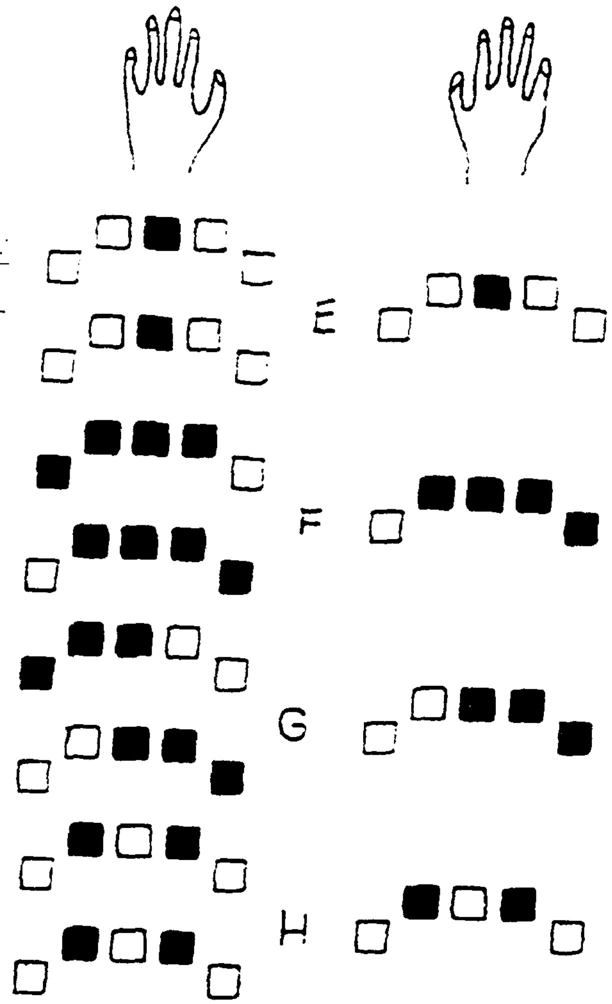

	Left hand: Single letter trials (Msec)			Left hand: Dual letter trials (Msec)			Right hand: Single letter trials (Msec)			Right hand: Dual letter trials (Msec)		
	HS	SPA	COV	HS	SPA	COV	HS	SPA	COV	HS	SPA	COV
E	429	463	45[illegible]	684	737	697	495	517	510	929	721	886
F	5421	630	541	890	945	759	631	731	652	1051	996	924
G	632	530	530	861	789	741	747	665	647	1142	1109	1053
H	514	529	497	735	712	688	579	600	642	946	1022	983

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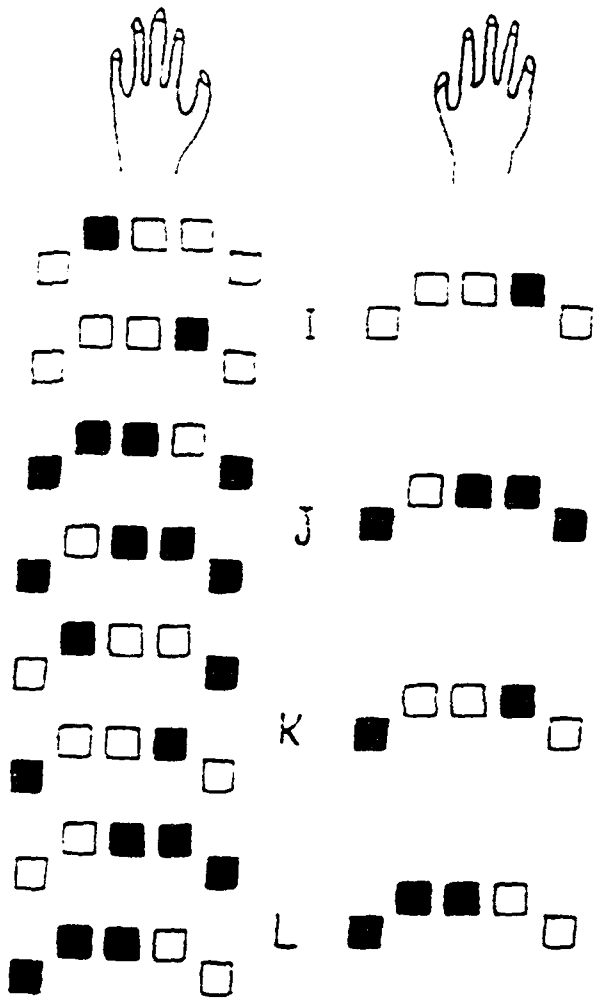
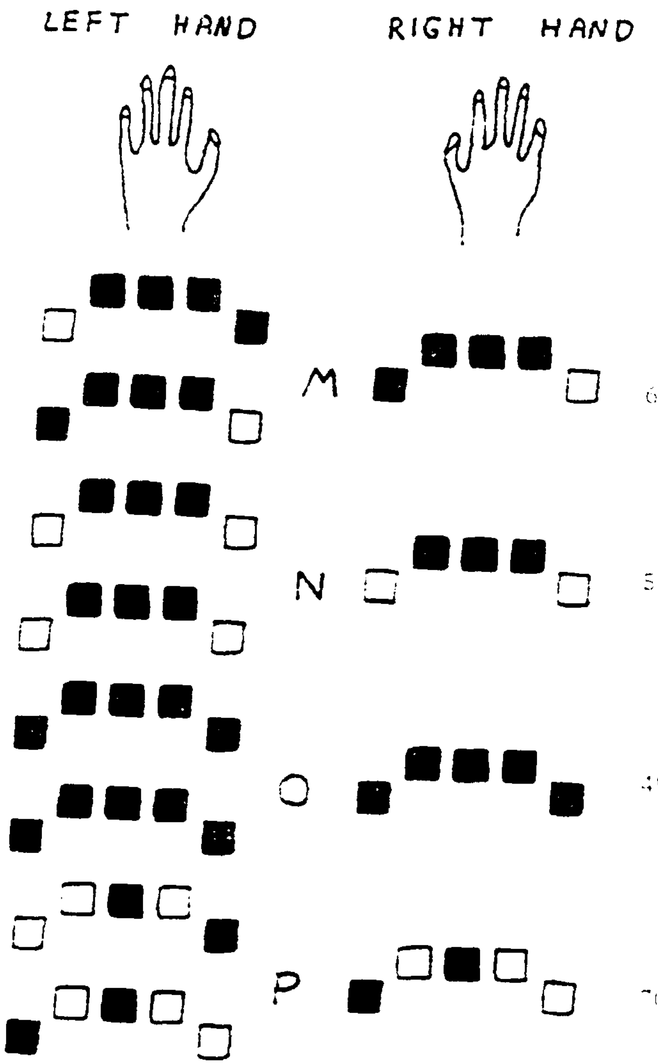


Single letter trials (Msec)			Dual letter trials (Msec)			Letter	Single letter trials (Msec)			Dual letter trials (Msec)		
HS	SPA	COV	HS	SPA	COV		HS	SPA	COV	HS	SPA	COV
454	557	557	758	763	686	I	551	596	613	946	905	902
566	581	540	722	980	714	J	612	834	688	1032	1126	979
711	780	564	1018	985	773	K	681	831	656	1074	1073	945
545	722	550	849	859	814	L	669	660	641	1185	1036	1012



	Left hand: Single letter trials (Msec)			Left hand: Dual letter trials (Msec)				Right hand: Single letter trials (Msec)			Right hand: Dual letter trials (Msec)		
	HS	SPA	COV	HS	SPA	COV		HS	SPA	COV	HS	SPA	COV
	[illegible]	[illegible]	558	1044	825	797	M	678	667	551	1109	1026	981
	475	464	531	806	701	734	N	594	555	[illegible]	954	994	[illegible]
	440	416	426	590	605	605	O	496	522	529	894	918	853
	663	[illegible]	524	884	1009	795	P	709	640	[illegible]	1041	[illegible]	925

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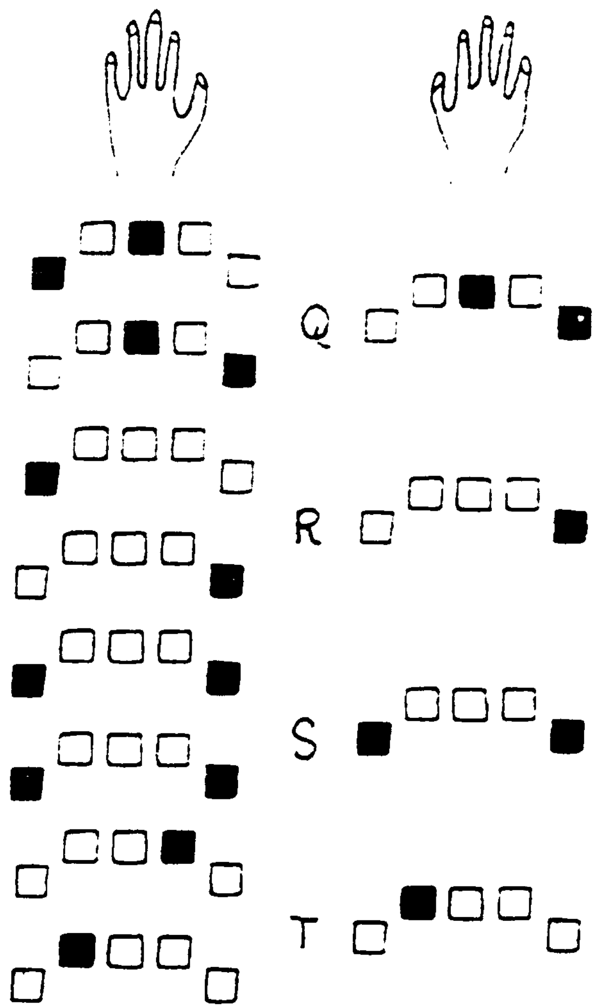

Left hand

Letter	Single letter trials (Msec) HS	SPA	CON	Dual letter trials (Msec) HS	SPA	CON
Q	691	663	664	989	990	735
R	488	508	476	747	816	626
S	512	509	473	811	697	727
T	494	503	425	699	733	700

Right hand

Letter	Single letter trials (Msec) HS	SPA	CON	Dual letter trials (Msec) HS	SPA	CON
Q	833	922	736	1243	1237	1045
R	565	591	521	1106	948	874
S	576	565	539	1113	1053	960
T	551	552	495	989	931	842

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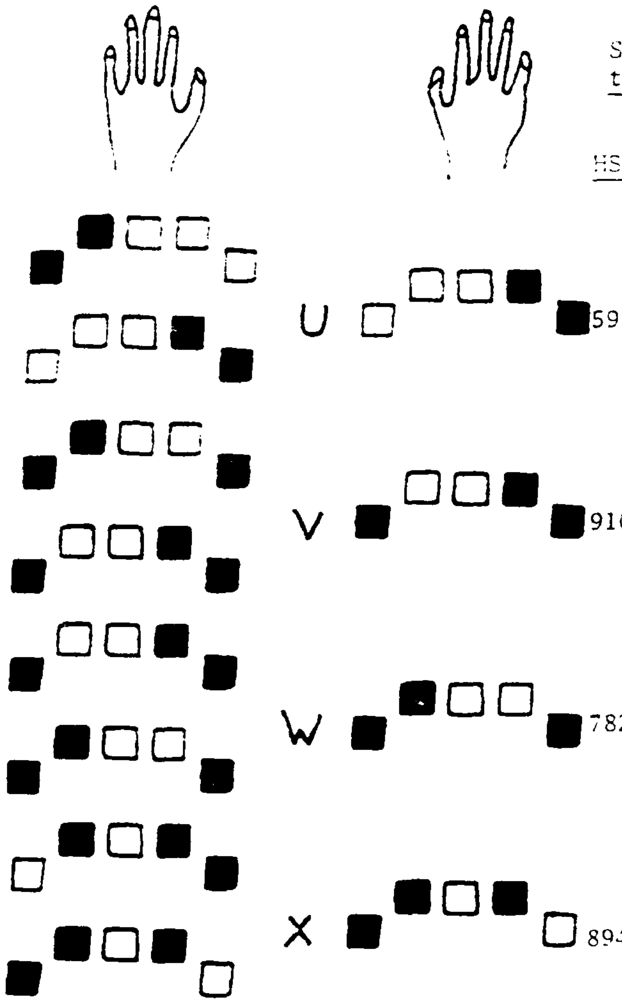
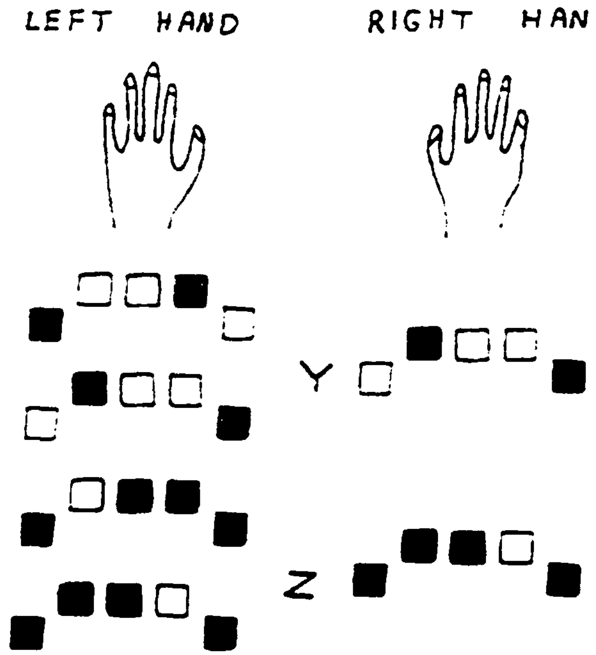


	Left hand: Single letter trials (Msec) HS	SPA	COV	Left hand: Dual letter trials (Msec) HS	SPA	COV	Right hand: Single letter trials (Msec) HS	SPA	COV	Right hand: Dual letter trials (Msec) HS	SPA	COV
U	533	324	490	824	758	701	597	606	609	1017	997	899
V	694	706	730	876	916	901	910	750	734	1166	1134	1067
W	733	643	662	1059	989	864	782	689	785	1191	1105	1038
X	699	953	815	998	1072	917	894	794	792	1208	1144	1162



	Left hand: Single letter trials (Msec)			Left hand: Dual letter trials (Msec)			Right hand: Single letter trials (Msec)			Right hand: Dual letter trials (Msec)		
	HS	SPA	COV	HS	SPA	COV	HS	SPA	COV	HS	SPA	COV
Y	754	695	336	976	963	741	653	751	649	1096	1175	993
Z	680	788	726	874	1043	727	783	982	756	1222	1200	853

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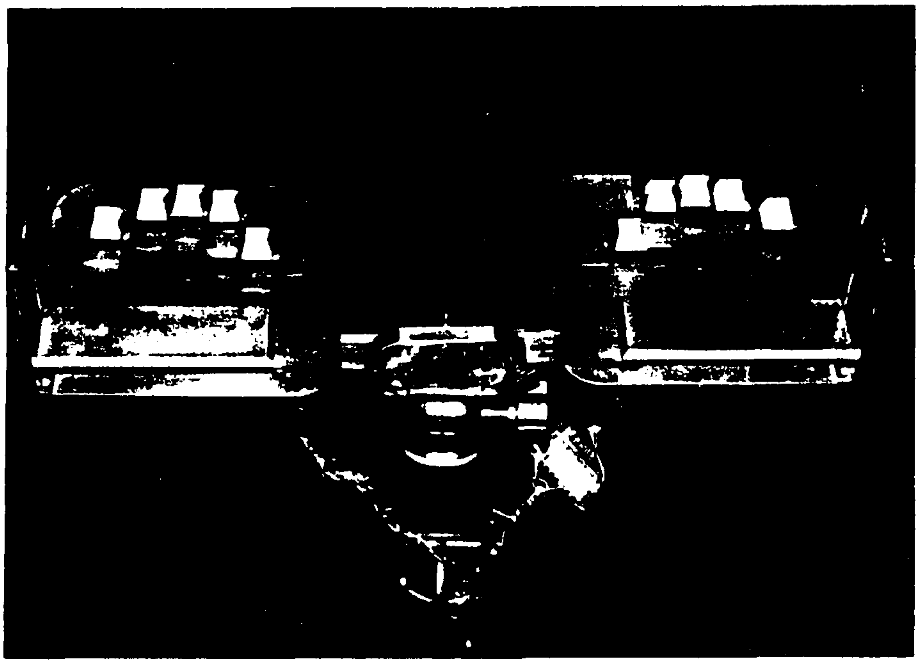

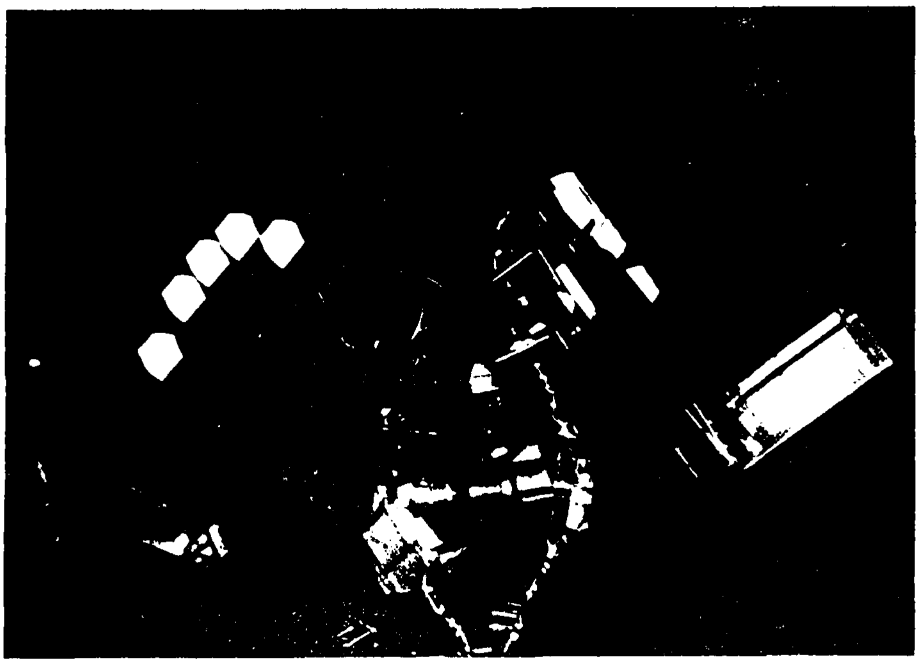

[illegible] The two hand chord keyboard in the horizontal and vertical positions.

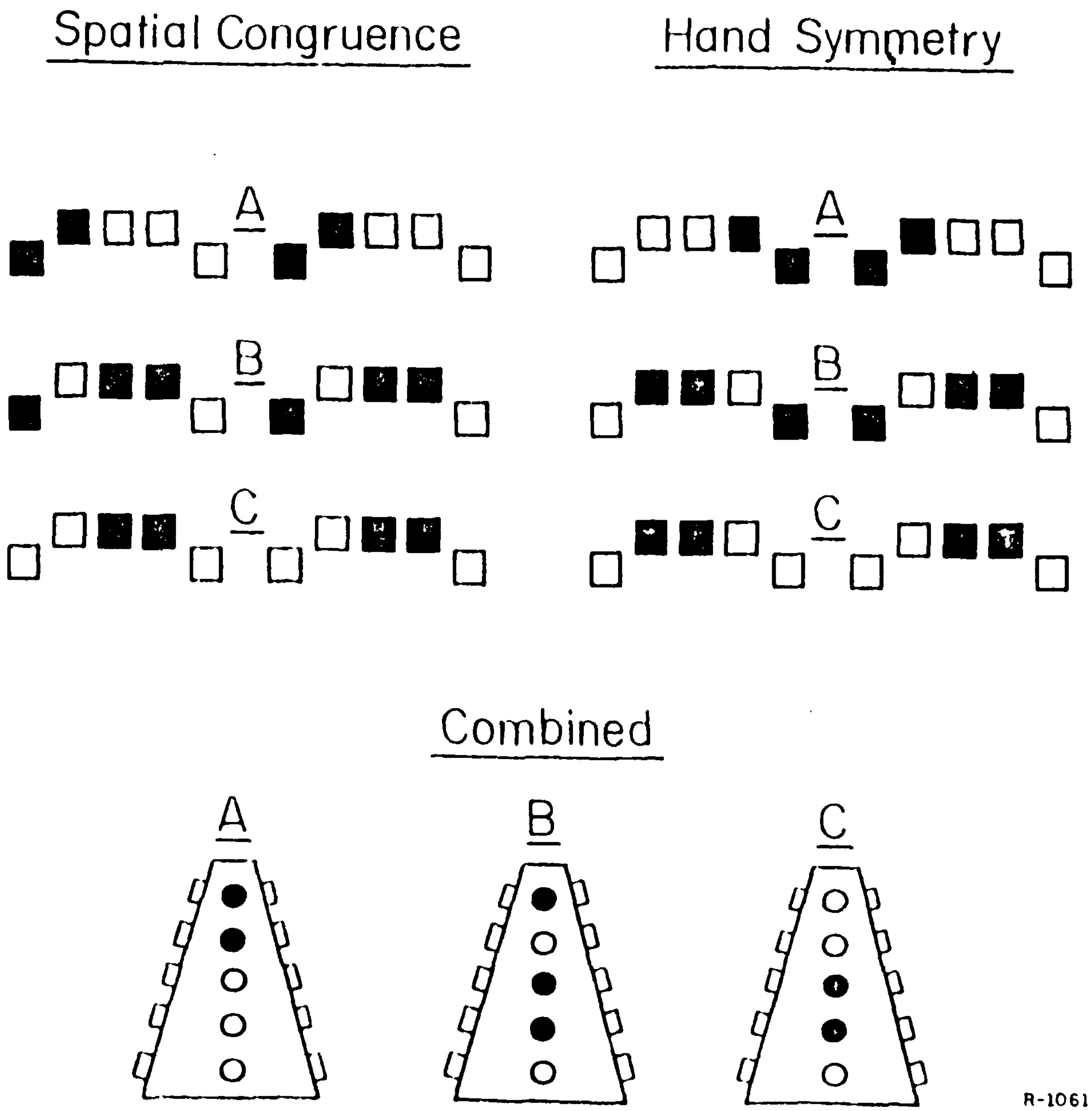

Figure 2 - Coding principles for associating letters with chord entries

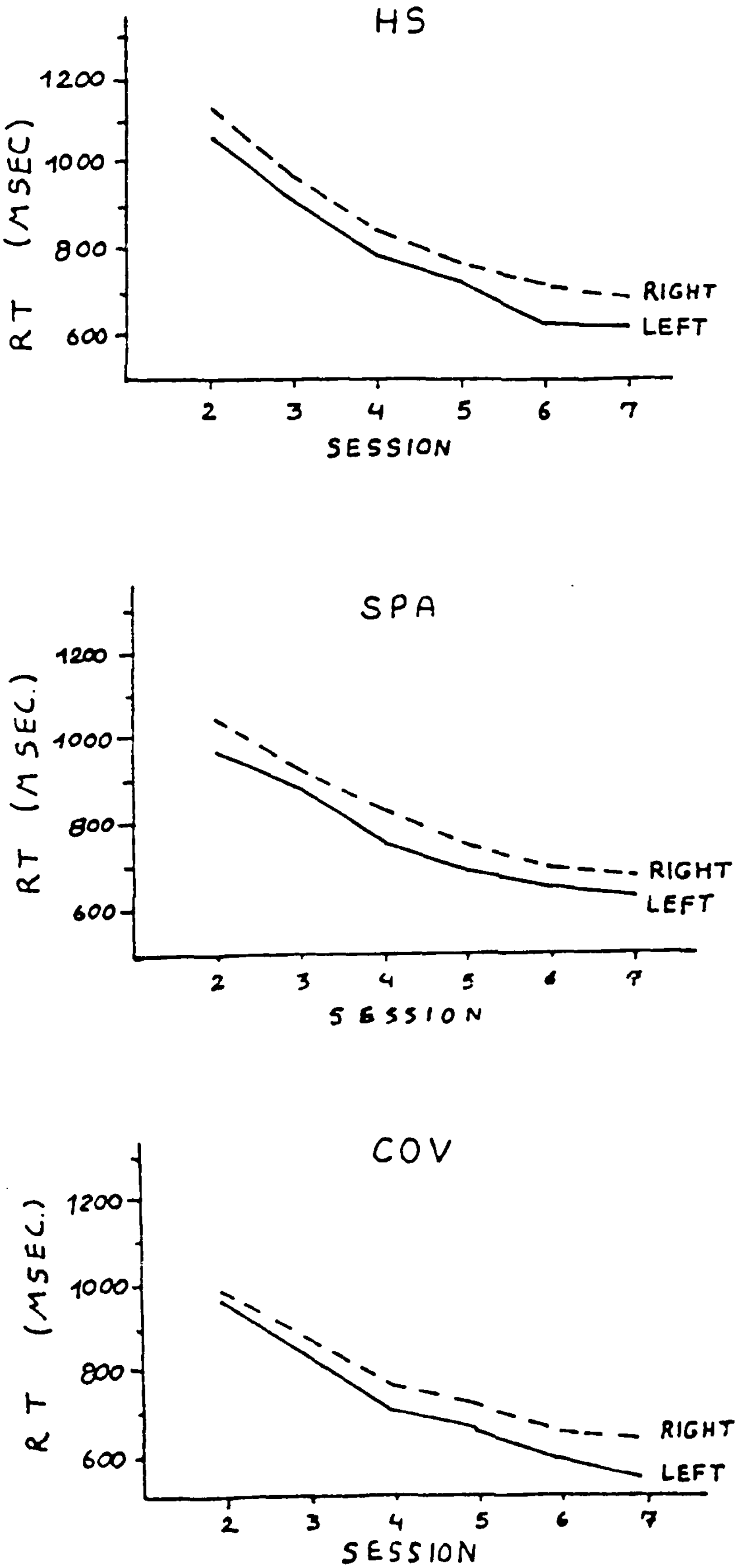

Figure 3 - Learning curves for single letter trials (mixed blocks) in the three experimental groups; Hand symmetry (HS), Spatial (SPA) and Combined (COV).

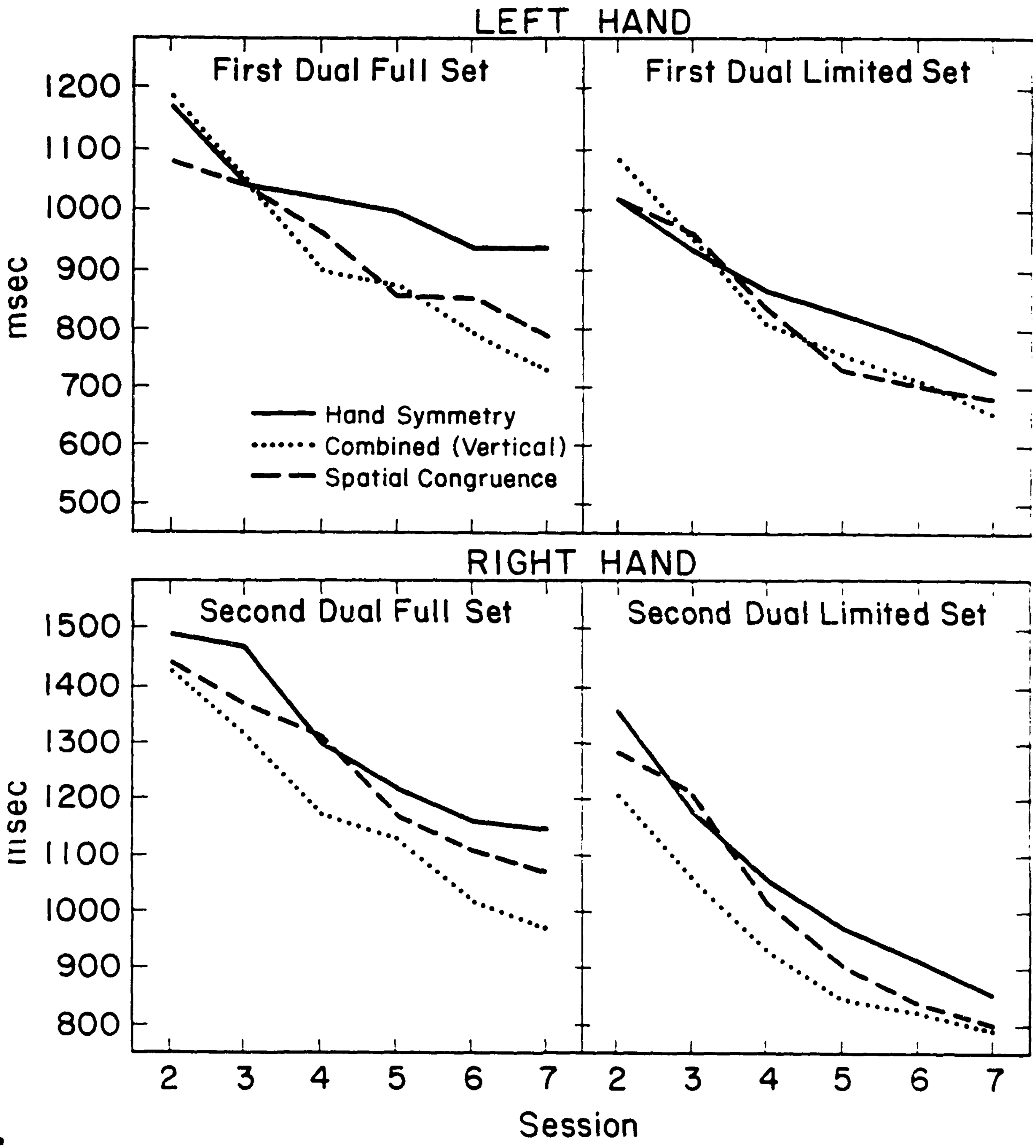

Figure 4. Response times for the left and right hands (first and second) in dual letter trials.

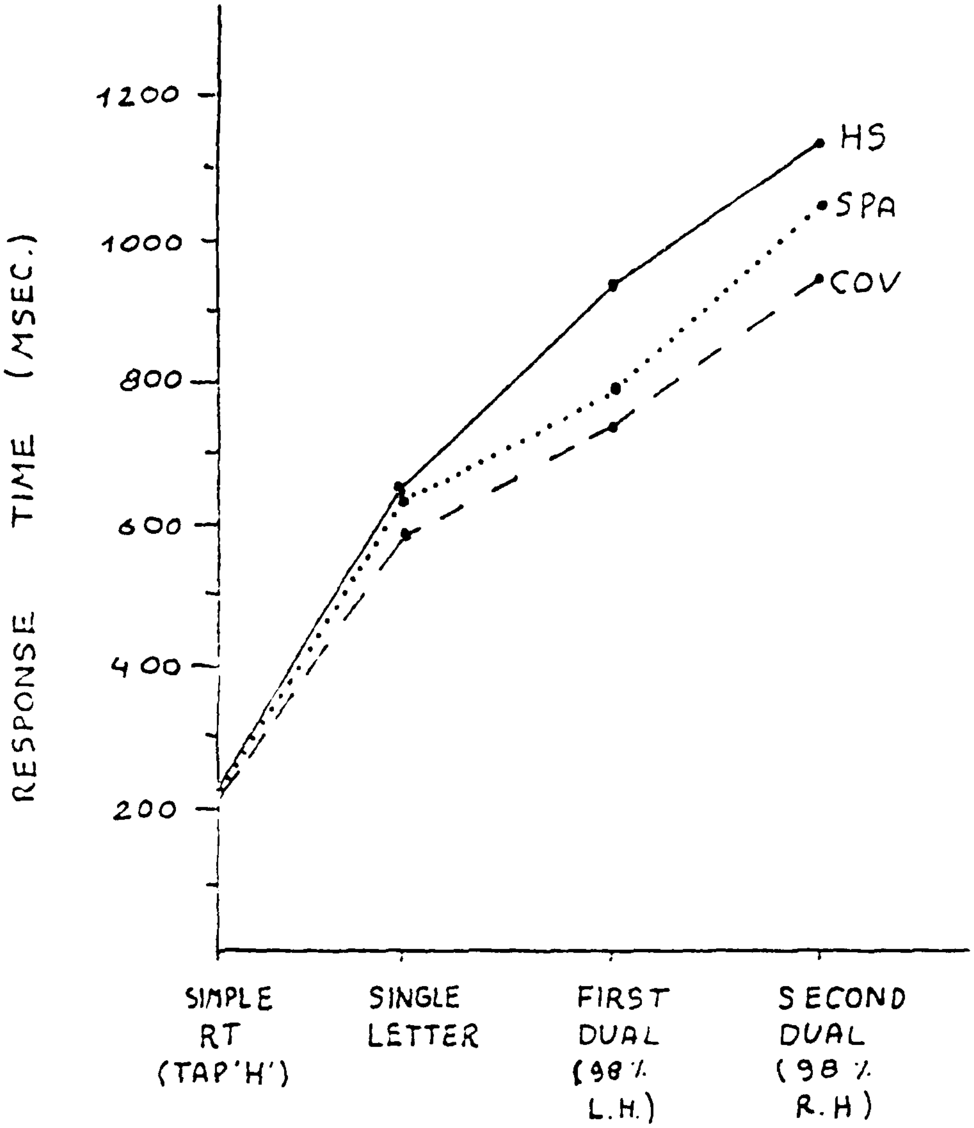

Figure 5 - Average response times of the three experimental groups in the 7th session (Mixed Blocks). Data is presented for simple RT, average across hands of single letter trials, and the first and second response in dual letter trials.

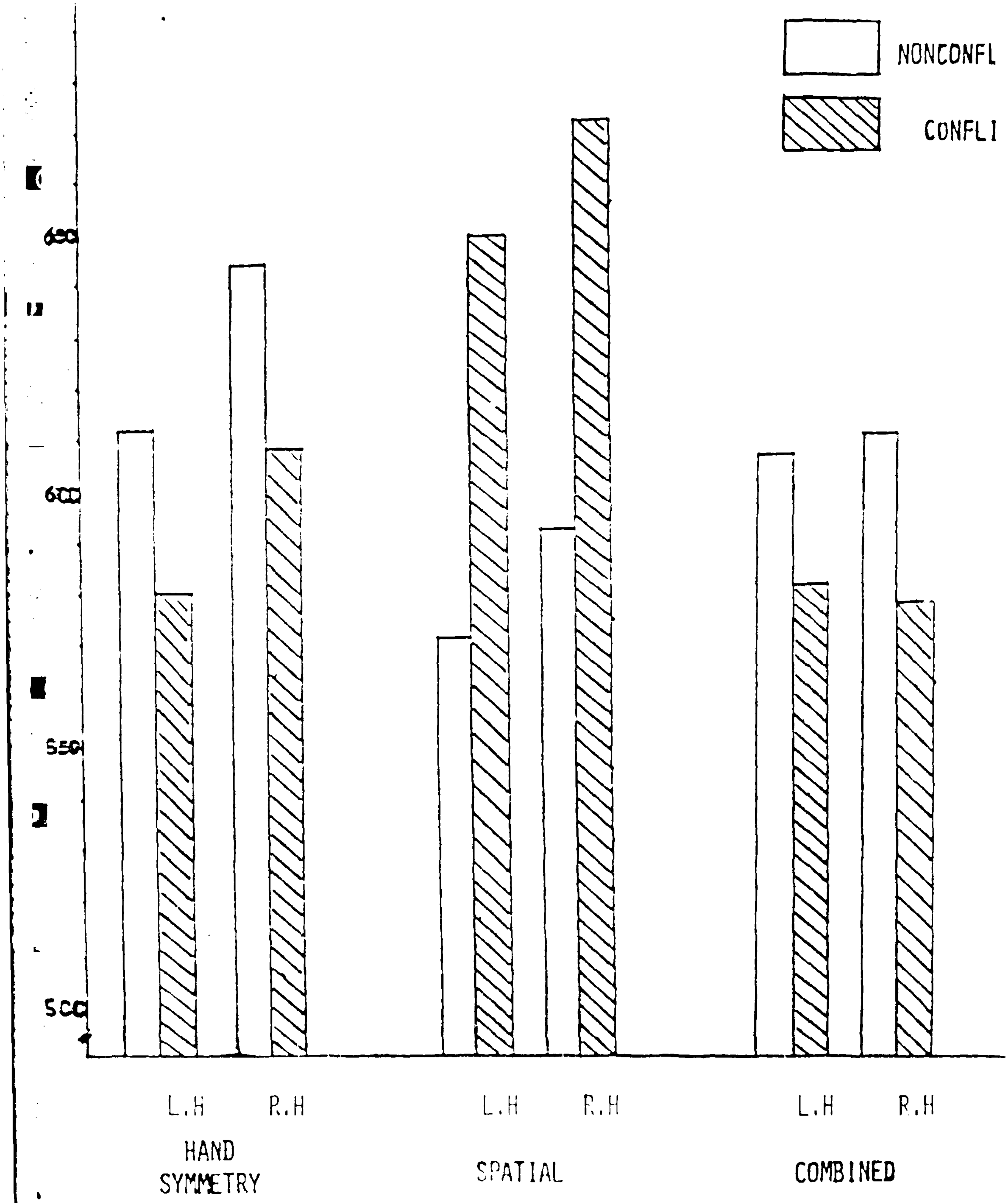

Figure 6 - Response times for pairs of same letters with conflicting and nonconflicting representations (dual limited set blocks. Meetings 3-7).

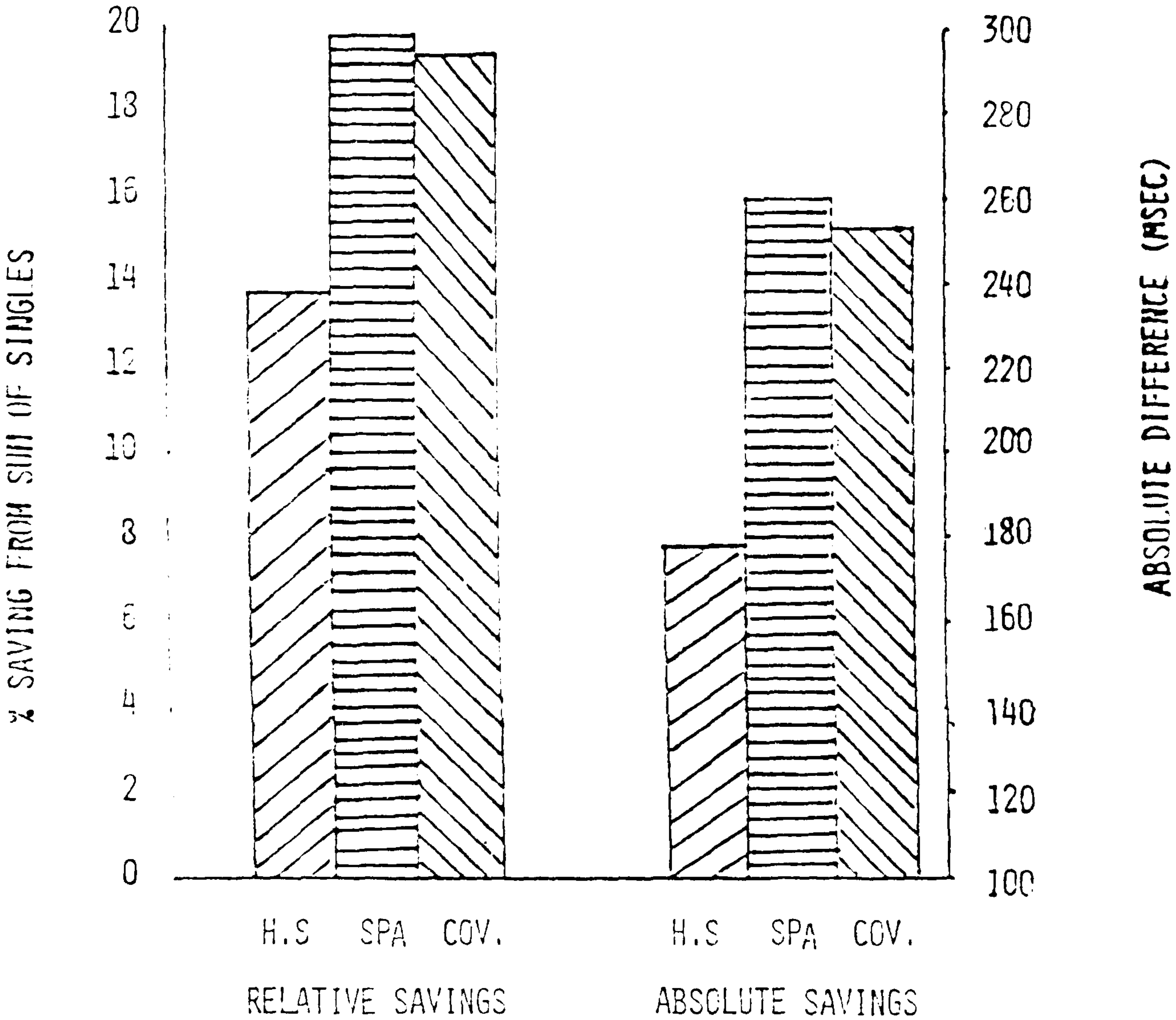

Figure 7 - Relative and absolute savings in parallel data entry (7th meeting, mixed blocks).

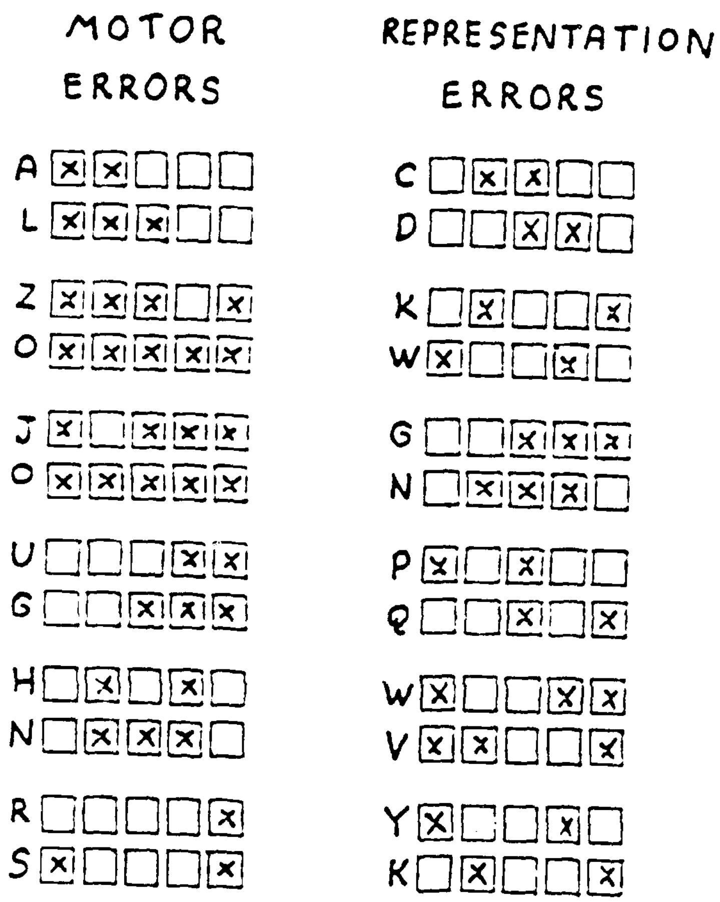

Figure 8: Examples from right hand entries of frequent motor and representation errors. The upper row in each example is the desired letter, the lower row is the actual typed letter.

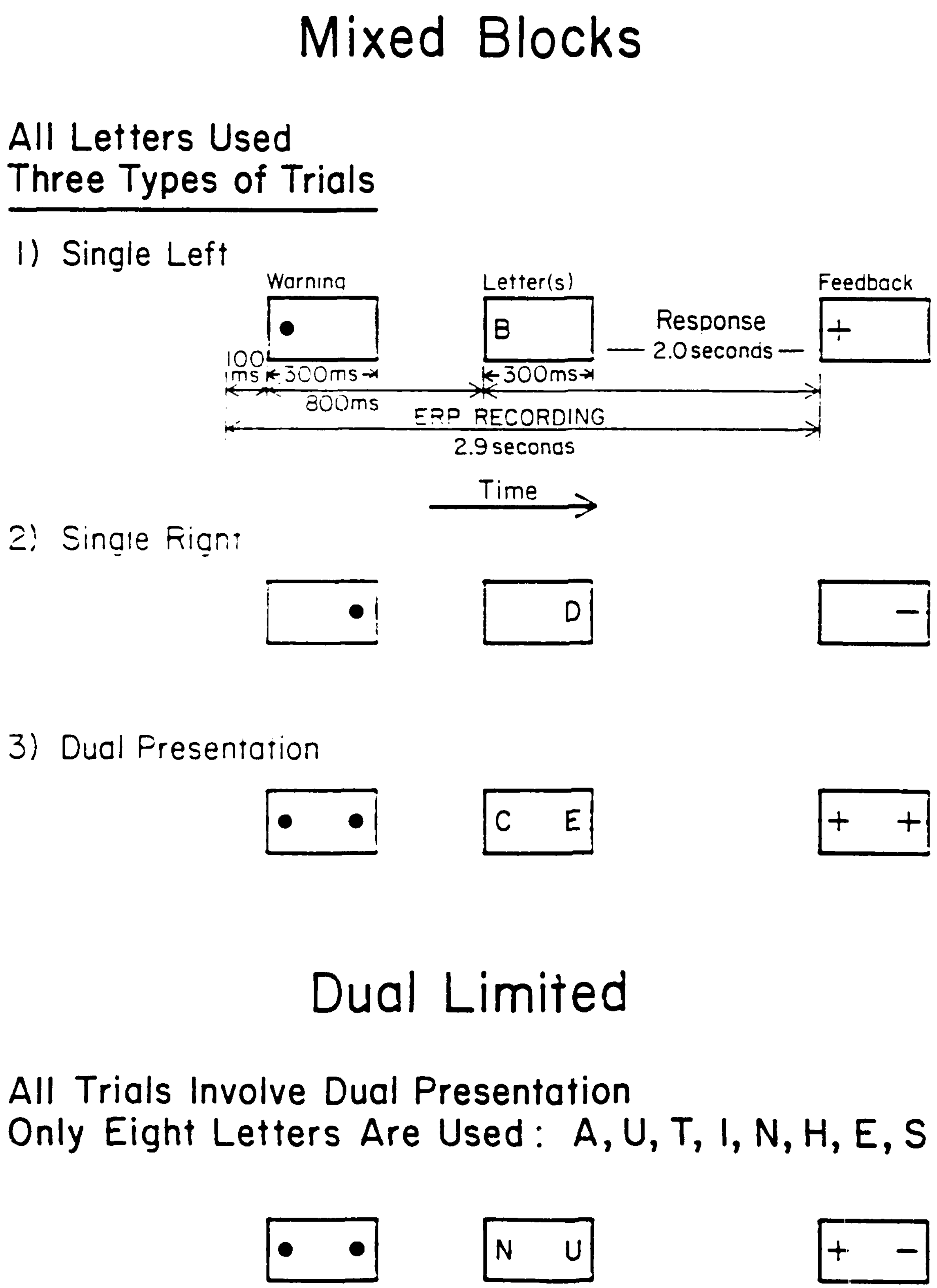

Fig. 9 The composition of mixed blocks and dual limited blocks are presented, along with the time sequence of a trial

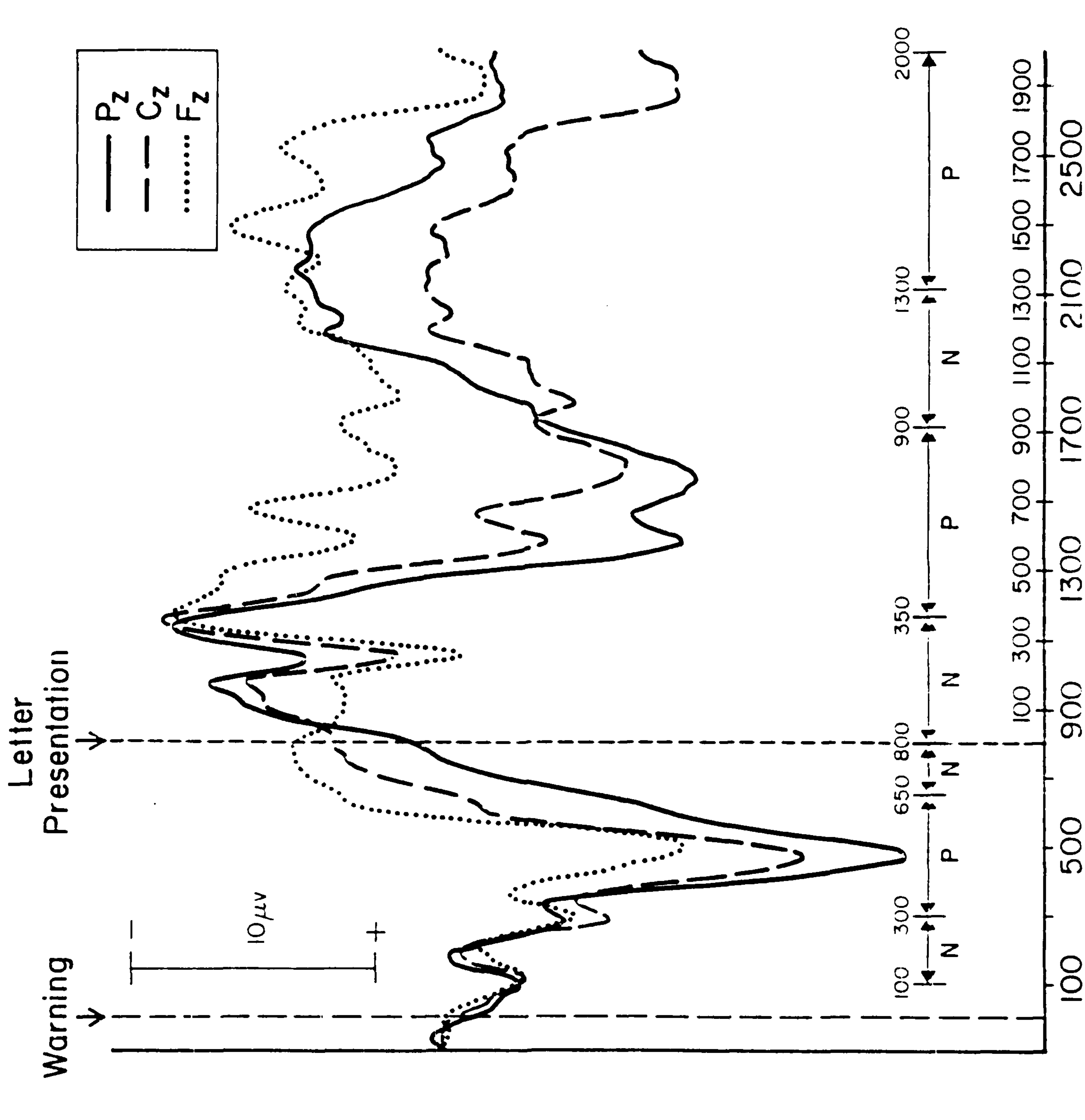

Fig. 10 Representative waveform from the three electrode sites from a single subject are presented, along with the time windows used in the analysis (session four, spatial condition, single left presentation).

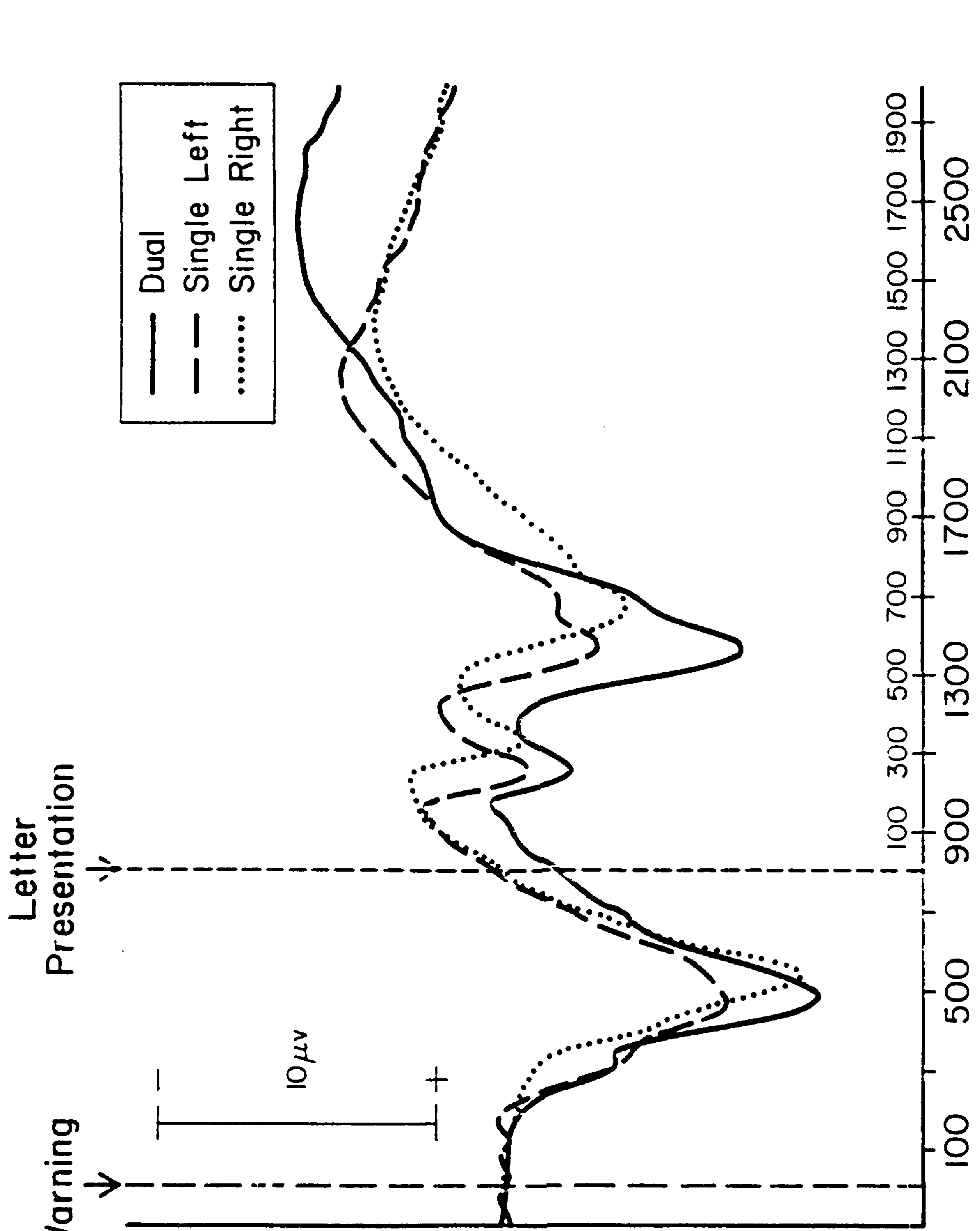

Fig. 11 Grand average waveforms (over all 15 subjects and 5 sessions) at Pz for the three conditions.

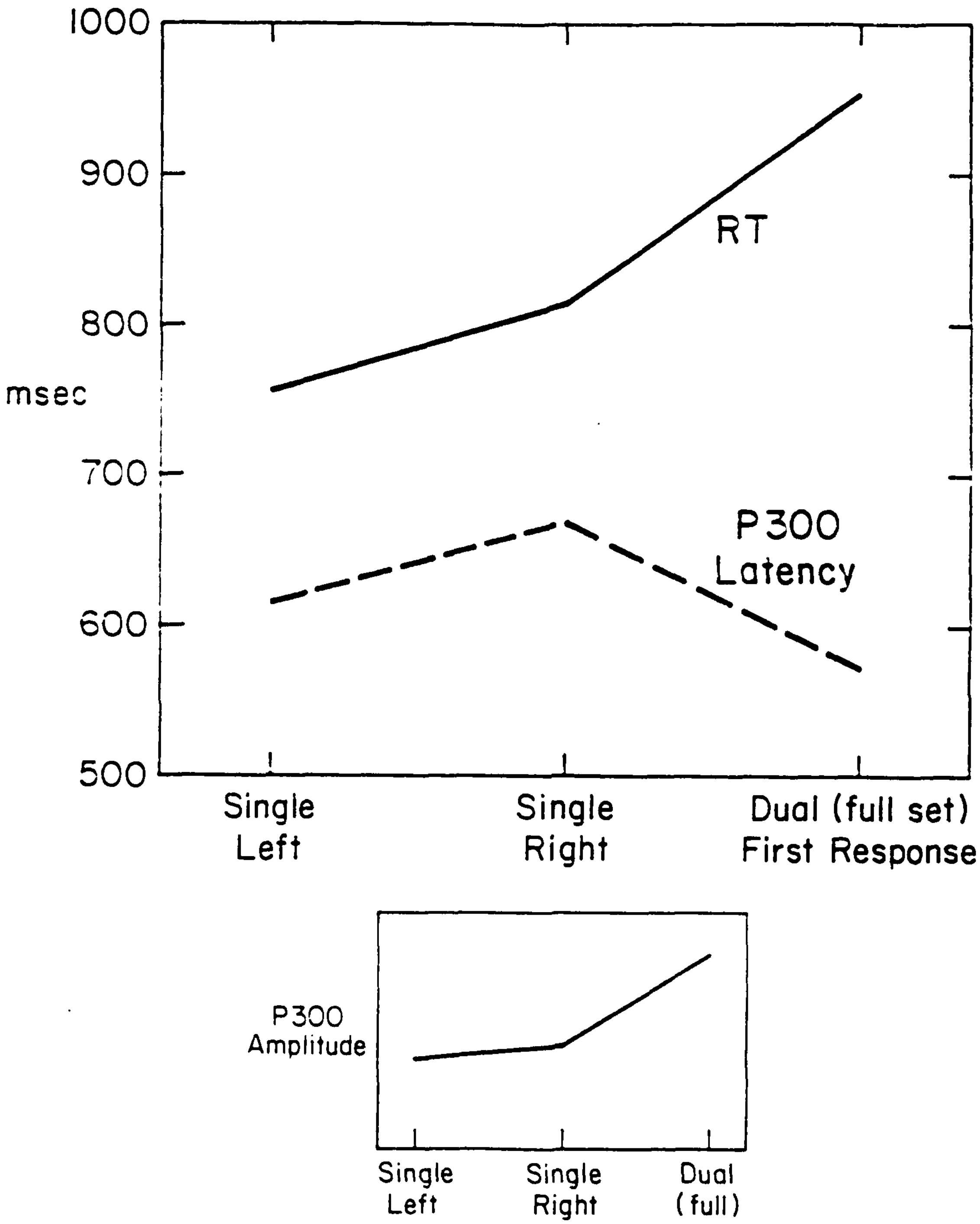

Fig. 12 RT and P300 latency for the three conditions (top) and P300 amplitude (bottom).

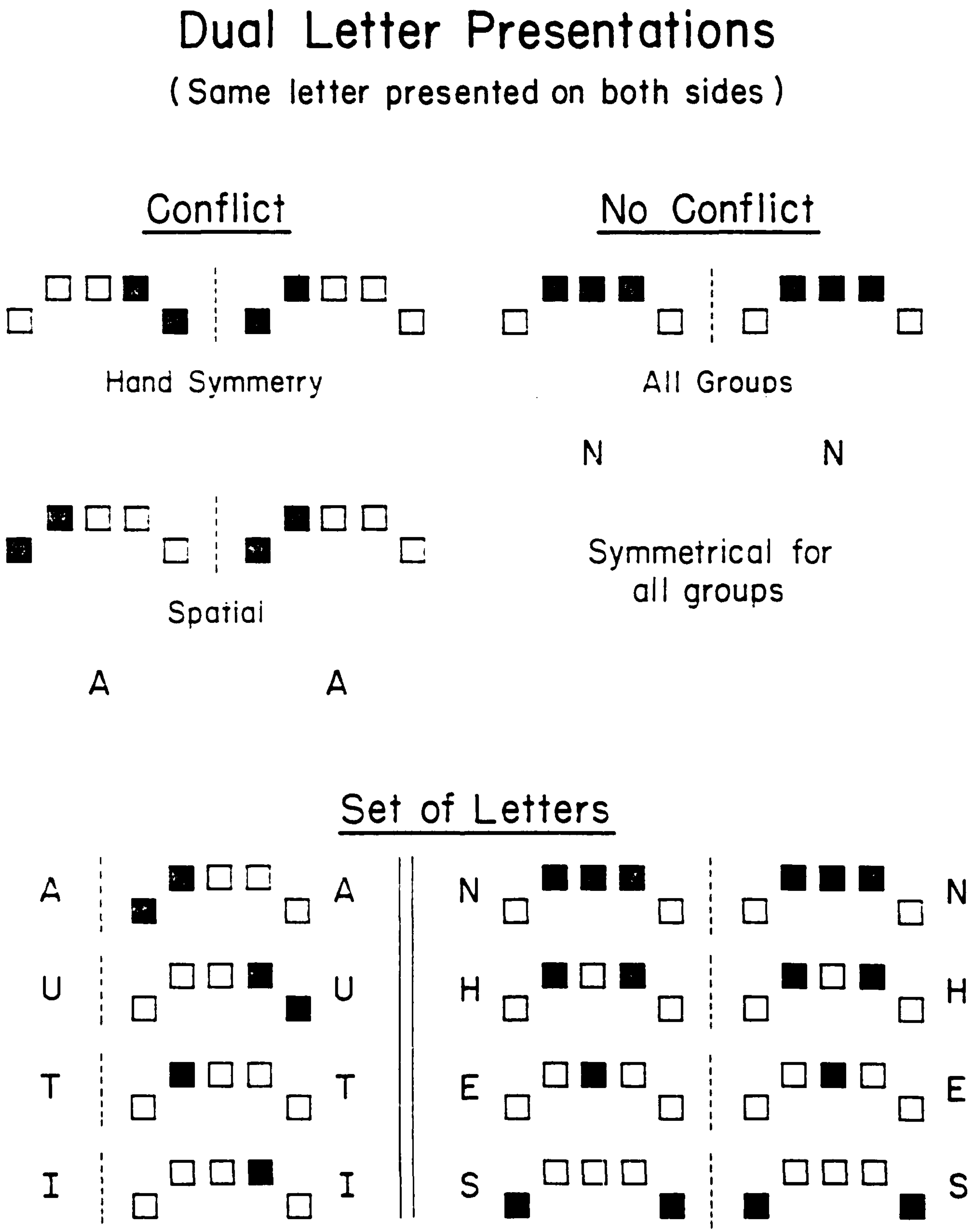

Fig. 13 Examples of conflict and no conflict (top) and letters that produce conflict and no conflict (bottom).

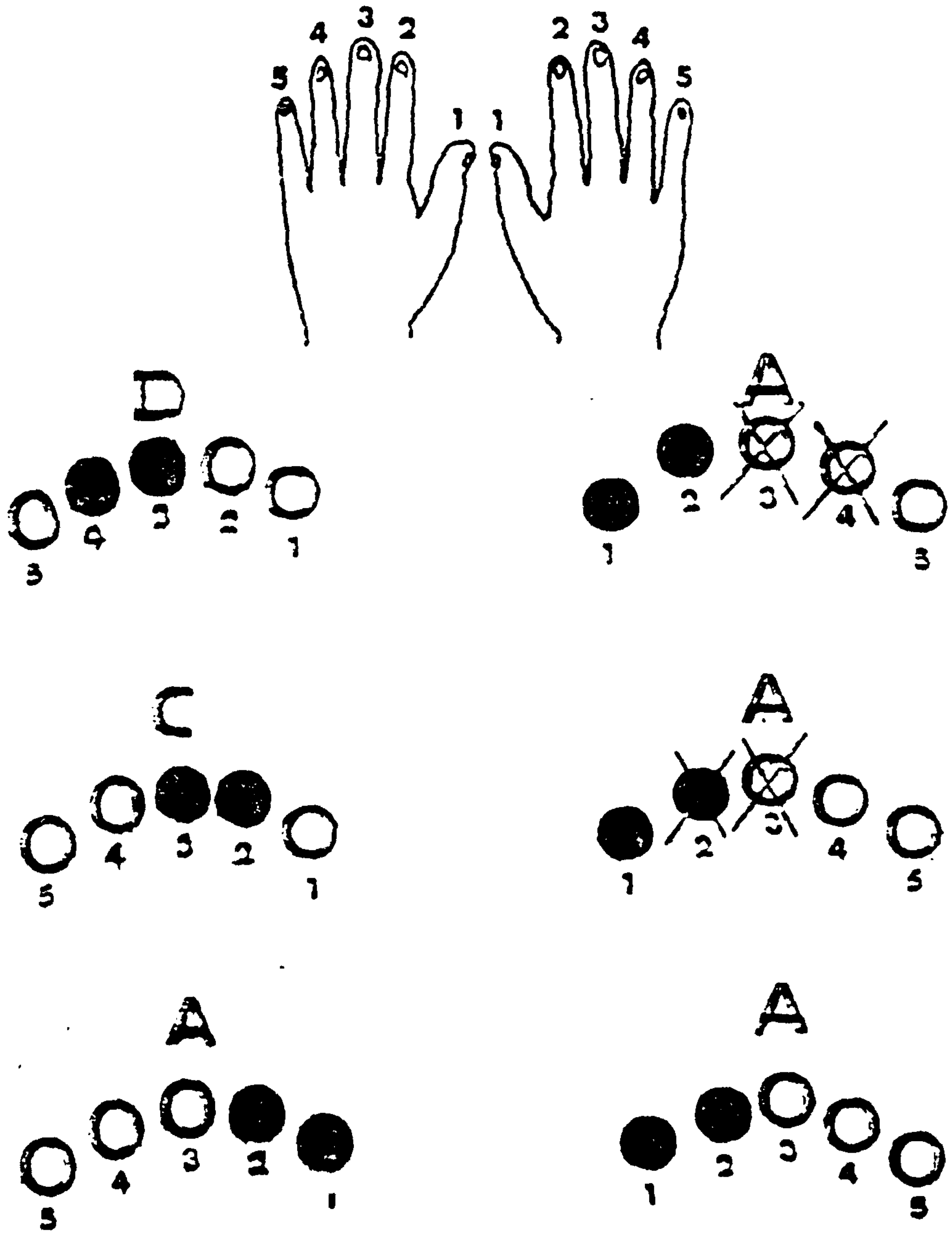

Fig. 14: Hypothetical conflicts due to involuntary symmetric activation of fingers.

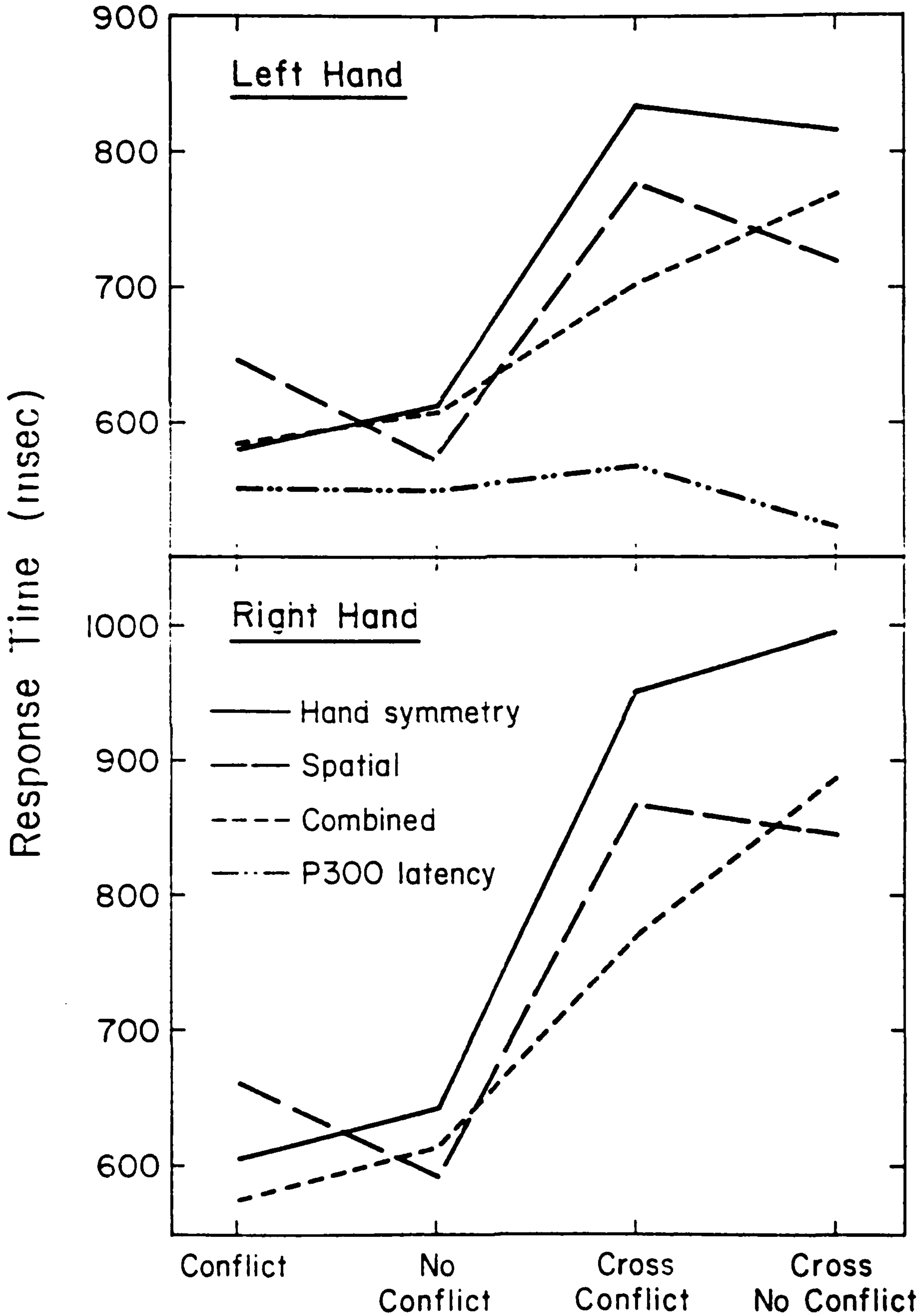

Fig. 15 RT and P300 latency for conflict conditions in each group.

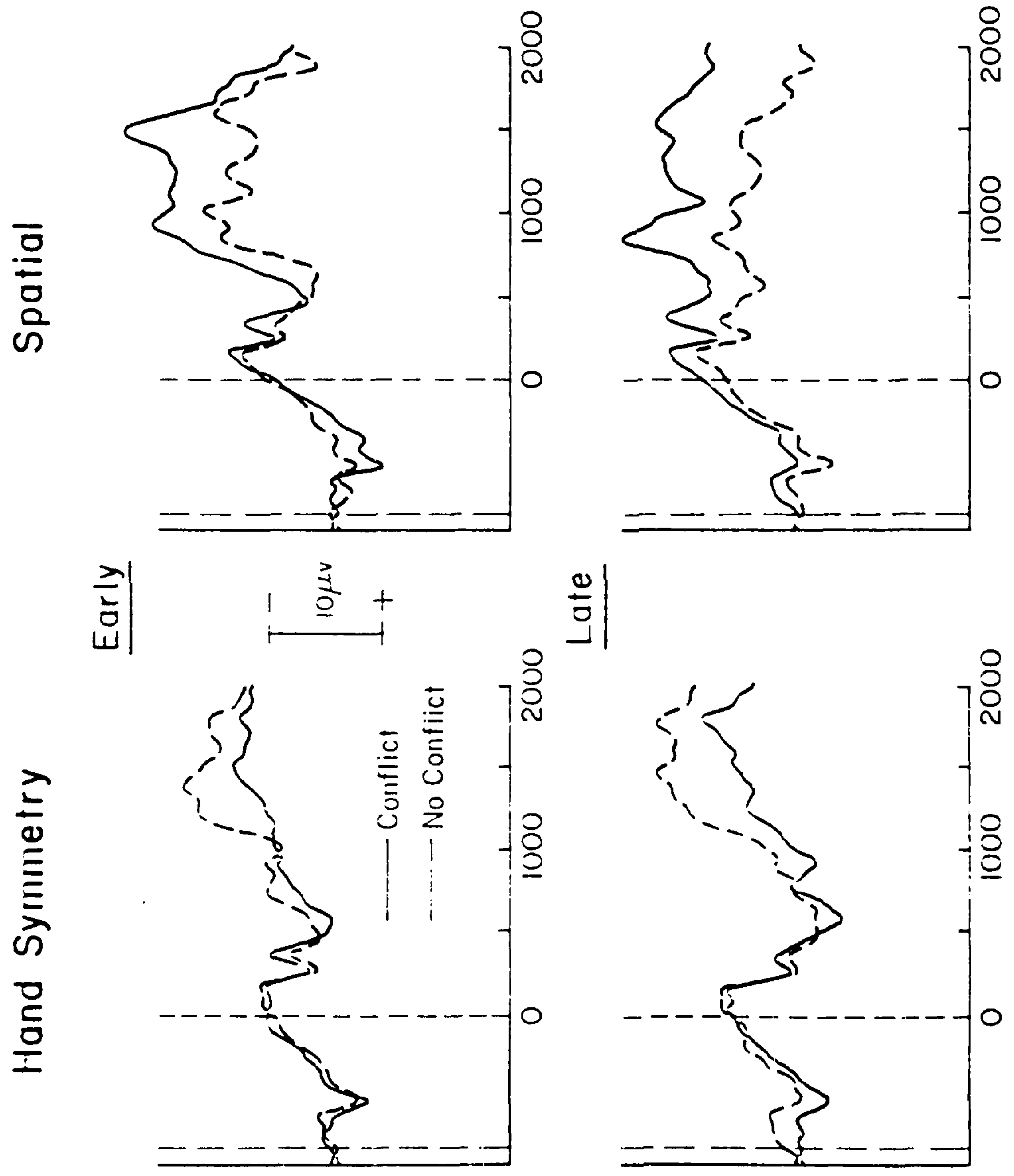

Fig. 16 Average waveforms at Cz for conflict and no conflict trials in early (first two) and late (last three) sessions.

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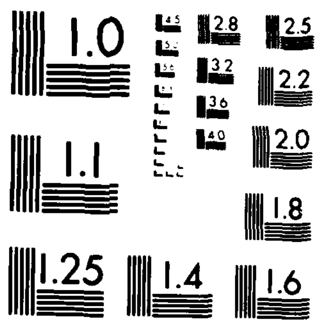

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